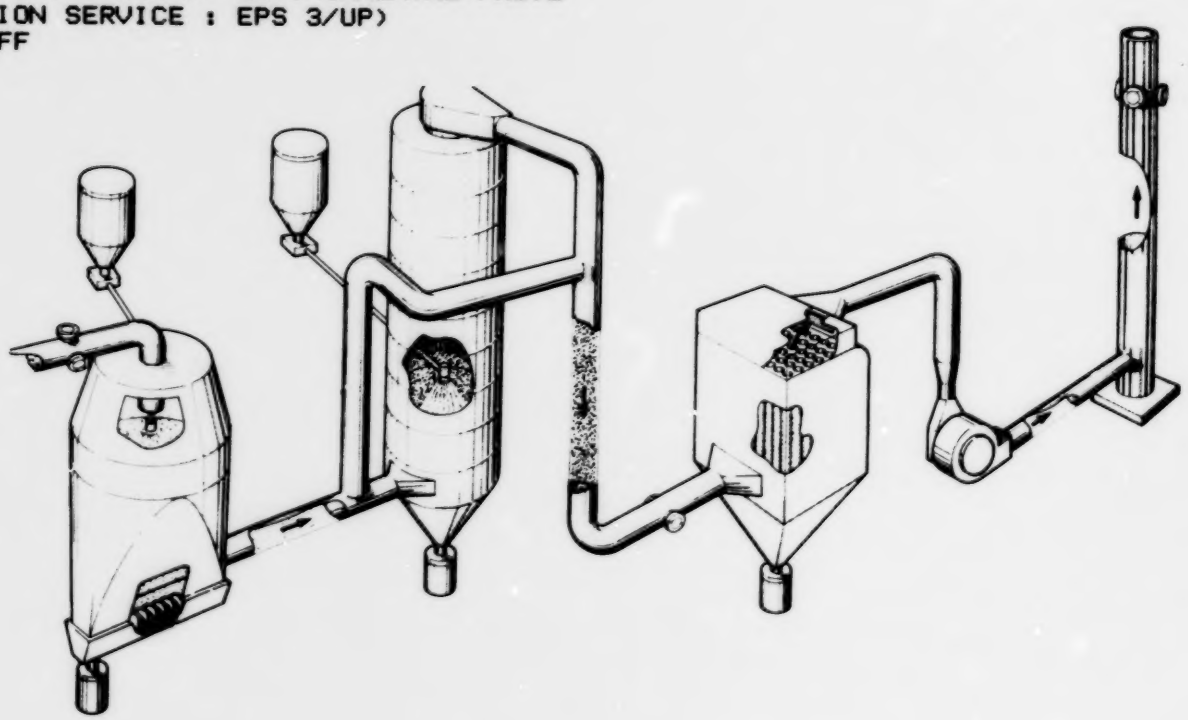
The National Incinerator Testing and Evaluation Program: Air Pollution Control Technology

Report EPS 3/UP/2
September 1986

Environment CANADA Environnement
20410601 VOL ISS 2 860900
EXC # 001
TD 169 R463
REPORT (CANADA. ENVIRONMENTAL PROTE
CTION SERVICE : EPS 3/UP)
OOFF



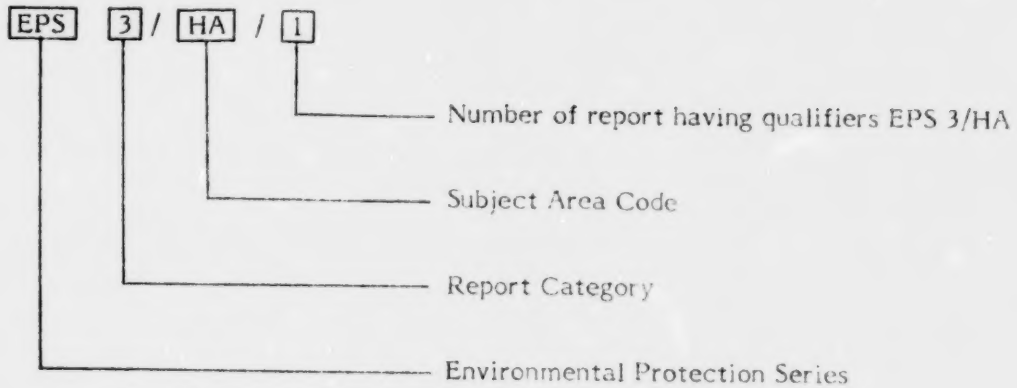
Environment Canada Environnement Canada

Canada

87-00441/

ENVIRONMENTAL PROTECTION SERIES

Sample Number:



Categories

1 Regulations/Guidelines/Codes of Practice
2 Problem Assessments and Control Options
3 Research and Technology Development
4 Literature Reviews
5 Surveys
6 Social, Economic and Environmental Impact Assessments
7 Surveillance
8 Policy Proposals & Statements
9 Manuals

Subject Areas

AG Agriculture
AP Airborne Pollutants
AT Aquatic Toxicity
CC Commercial Chemicals
CE Consumers and the Environment
FP Food Processing
HA Hazardous Wastes
IC Inorganic Chemicals
MA Marine Pollution
MM Mining & Mineral Processing
NR Northern Regions
PF Paper and Fibres
PG Power Generation
PN Petroleum and Natural Gas
SP Oil & Chemical Spills
SRM Standard Reference Methods
TS Transportation
UP Urban Pollution

New subject areas and codes are introduced as they become necessary. A list of EPS reports may be obtained from Environmental Protection Publications, Conservation and Protection, Environment Canada, Ottawa, Ontario, Canada, K1A 0E7.

THE NATIONAL INCINERATOR TESTING AND EVALUATION PROGRAM: AIR POLLUTION CONTROL TECHNOLOGY

Summary Report

A joint program conducted by:

Flakt Canada Ltd.

and

Environment Canada

Report EPS 3/UP/2
September 1986

REVIEW NOTICE

This report has been reviewed by the Environmental Protection Directorate, Conservation and Protection, and approved for publication. Approval does not necessarily signify that the contents reflect the views and policies of Environment Canada. Mention of trade names or commercials products does not constitute recommendation or endorsement for use.

READERS COMMENTS

Readers who wish to comment on the content of this report should address their comments to:

Mr. R. Klicius or Mr. A. Finkelstein
Industrial Programs Branch
Environmental Protection Directorate
Conservation and Protection
Environment Canada
Ottawa, Ontario
K1A 1C8

© Minister of Supply and Services Canada 1986
Cat. No. En 49-8/3-2E
ISBN 0-662-14844-4
BEAUREGARD PRESS LIMITED

ABSTRACT

Environment Canada, through a joint program with Flakt Canada Ltd., conducted a series of comprehensive tests on two pilot-scale air pollution control systems. The tests were designed to determine the capability of these systems to control emissions of dioxins, other trace organics, metals and acid gases. Field testing was completed in August/September, 1985, for two different designs: one using a wet-dry scrubber (spray-dryer) plus fabric filter and the other using a dry scrubber plus fabric filter. The systems were designed by Flakt Canada Ltd. and were erected adjacent to the mass burning incinerator in Québec City.

Many different operating conditions were tested to identify optimum removal efficiencies for all pollutants of concern. Final results were very significant. Flue gas temperature was found to be an important operating variable for achieving high removal efficiency for many of the pollutants measured. Appropriate operating conditions were identified to obtain extremely high removal efficiencies for dioxins and furans (>99%), other trace organics (>98%), heavy metals, including arsenic and lead (>99.9%) and up to 97% for mercury. Excellent removal (>95%) was also obtained for acid gases, i.e. hydrogen chloride and sulphur dioxide.

RÉSUMÉ

Environnement Canada, en collaboration avec Flakt Canada Ltd., a réalisé un programme détaillé d'essais sur deux systèmes pilotes de dépollution. Ces essais étaient destinés à déterminer l'efficacité de ces systèmes pour éliminer les émissions atmosphériques de dioxines, d'autres composés organiques présents en traces, de métaux et de gaz acides. Les essais ont été réalisés en août et septembre 1985. Deux procédés différents ont été employés: l'un par voie humide et sèche, avec pulvérisation et séchage dans un réacteur, et l'autre, par voie sèche, faisant appel à un réacteur. Dans les deux cas, un dépoussiéreur filtrant suivait le réacteur. Les systèmes ont été conçus par Flakt Canada Ltd. et installés près de l'incinérateur de déchets non conditionnés de la ville de Québec.

Les essais ont été effectués dans de nombreuses conditions opératoires différentes afin de déterminer le meilleur rendement d'élimination de chacun des polluants visés par l'étude. Les résultats finals ont été très concluants. On a constaté que la température des gaz de combustion était une importante variable opératoire permettant d'obtenir un rendement d'élimination élevé pour une grande partie des pollutants mesurés. Dans certaines conditions opératoires bien définies, des rendements d'élimination très élevés ont été obtenus: plus de 99% pour les dioxines et les furannes, plus de 98% pour d'autres composés organiques présents en traces, et plus de 99,9% pour les métaux lourds, y compris l'arsenic et le plomb, et jusqu'à 97% pour le mercure. Dans le cas des gaz acides, c'est-à-dire du chlorure d'hydrogène et du dioxyde de soufre, le rendement a été également excellent (plus de 95%).

TABLE OF CONTENTS

		Page
ABSTRACT		iii
LIST OF FIGURES		vii
LIST OF TABLES		ix
ACKNOWLEDGEMENTS		x
1	INTRODUCTION	1
2	INCINERATOR DESCRIPTION	3
3	PILOT PLANT DESCRIPTION	6
3.1	Scrubbing Processes	6
3.2	Plant Design	7
3.3	Pilot Plant Components	7
3.3.1	Dry System	9
3.3.2	Wet-Dry System	11
3.3.3	Fabric Filter	11
3.3.4	Process Control	11
4	SAMPLING AND ANALYTICAL PROTOCOLS	12
4.1	Testing Program Considerations	12
4.2	Manual Sampling	13
4.3	Continuous Gas Monitors	16
4.4	Process Data and Ash Samples	18
4.5	Analytical Procedures	18
4.5.1	Organic Analysis	19
4.5.2	Metals Analyses	21
4.5.3	Chloride Analysis	22
4.5.4	Leachability Tests	22
4.6	Quality Assurance and Quality Control	22
5	TEST PROGRAM DESCRIPTION	25
5.1	Characterization Tests	25
5.2	Results of Characterization Tests	28
5.3	Selection of Performance Test Conditions	28
6	PERFORMANCE TEST RESULTS	31
6.1	Comparison of Test Data within Each Pair of Runs	31
6.2	Test Condition Averages	32
6.2.1	Incineration and Pilot Plant Operating Data	32
6.2.2	Conventional Flue Gas Data	40

		Page
7	DIOXIN/FURAN RESULTS	43
7.1	Dioxins in Flue Gas	43
7.2	Furans in Flue Gas	45
7.3	Dioxins in Hopper Ashes	48
7.4	Furans in Hopper Ashes	51
8	OTHER ORGANIC RESULTS	56
8.1	Other Organics in Flue Gas	56
8.2	Other Organics in Hopper Ashes	57
9	METALS RESULTS	60
9.1	Metals in Flue Gas	60
9.2	Metals in Hopper Ashes	61
10	ACID GAS EMISSIONS	64
10.1	Typical Hydrogen Chloride and Sulphur Dioxide Variations	64
10.2	Acid Gas Data and Removal Efficiencies	64
10.3	Stoichiometric Ratio and Lime Addition Rate	67
10.4	Effect of Ash Recycle	70
11	CONCLUSIONS AND RECOMMENDATIONS	71
11.1	Conclusions	71
11.2	Recommendations	72
REFERENCES		75
APPENDIX -	SYMBOLS, ABREVIATIONS AND HOMOLOGUES OF POLYCHLORINATED DIBENZODIOXINS AND DIBENZOFURANS	79

LIST OF FIGURES

Figure		Page
1	QUEBEC INCINERATOR SCHEMATIC CROSS-SECTION	4
2	FLAKT'S PILOT PLANT MAIN EQUIPMENT COMPONENTS	8
3	INCINERATOR GAS SLIP STREAM TAKE-OFF ARRANGEMENT	9
4	FLAKT'S DRY SYSTEM	10
5	FLAKT'S WET-DRY SYSTEM	10
6	SCHEMATIC OF SAMPLING TRAINS	14
7	SCHEMATIC OF ORGANIC SAMPLE PROCESSING AND ANALYSIS	20
8	PARAMETERS MEASURED DURING CHARACTERIZATION TESTING	26
9	SAMPLING/DATA PARAMETERS FOR PERFORMANCE TESTING	30
10	PERFORMANCE TEST RESULTS (PT-12, 13) - DRY SYSTEM AT 110°C	33
11	PERFORMANCE TEST RESULTS (PT-3, 4) - DRY SYSTEM AT 125°C	34
12	PERFORMANCE TEST RESULTS (PT-2, 11) - DRY SYSTEM AT 140°C	35
13	PERFORMANCE TEST RESULTS (PT-5, 6) - DRY SYSTEM AT >200°C	36
14	PERFORMANCE TEST RESULTS (PT-7, 8) - WET-DRY SYSTEM AT 140°C (NO RECYCLE)	37
15	PERFORMANCE TEST RESULTS (PT-9, 10) - WET-DRY SYSTEM AT 140°C (WITH RECYCLE)	38
16	PCDD CONCENTRATIONS IN FLUE GAS	44
17	PCDD HOMOLOGUE DISTRIBUTION IN FLUE GAS	46
18	PCDF CONCENTRATIONS IN FLUE GAS	47
19	PCDF HOMOLOGUE DISTRIBUTION IN FLUE GAS	49
20	PCDD CONCENTRATIONS IN HOPPER ASHES	50
21	PCDD HOMOLOGUE DISTRIBUTION IN HOPPER ASHES	52
22	PCDF CONCENTRATIONS IN HOPPER ASHES	53
23	PCDF HOMOLOGUE DISTRIBUTION IN HOPPER ASHES	54

LIST OF FIGURES (Cont'd)

Figure		Page
24	FLUE GAS CONCENTRATIONS OF CB, CP, PCB AND PAH	58
25	CB, CP, PCB AND PAH CONCENTRATIONS IN HOPPER ASHES	59
26	METALS IN HOPPER ASHES	62
27	TYPICAL HYDROGEN CHLORIDE AND SULPHUR DIOXIDE VARIATIONS DURING PERFORMANCE TESTS	65
28	HYDROGEN CHLORIDE AND SULPHUR DIOXIDE REMOVAL EFFICIENCIES VERSUS STOICHIOMETRIC RATIO AT DIFFERENT TEMPERATURES FOR DRY SYSTEM	68
29	SULPHUR DIOXIDE REMOVAL VERSUS TEMPERATURE AT DIFFERENT STOICHIOMETRIC RATIOS	69
30	HYDROGEN CHLORIDE AND SULPHUR DIOXIDE REMOVAL VERSUS STOICHIOMETRIC RATIO WITH AND WITHOUT RECYCLE	70

LIST OF TABLES

Table		Page
1	DESCRIPTION OF ANALYZERS FOR CONTINUOUS GAS MONITORING	17
2	SUMMARY OF CHARACTERIZATION TEST CONDITIONS	25
3	SELECTION OF PERFORMANCE TEST CONDITIONS	28
4	SUMMARY OF PERFORMANCE TEST CONDITIONS	31
5	SUMMARY OF KEY OPERATING PARAMETERS	39
6	FLUE GAS FLOW RATES	40
7	COMBUSTION GAS COMPOSITION AT OUTLET	41
8	PARTICULATE CONCENTRATION AT INLET	41
9	PROPORTION OF ASH COLLECTED IN EACH VESSEL	42
10	PCDD CONCENTRATIONS IN FLUE GAS AND EFFICIENCY OF REMOVAL	43
11	PCDF CONCENTRATIONS IN FLUE GAS AND EFFICIENCY OF REMOVAL	47
12	PCDD CONCENTRATIONS IN ASH	50
13	PCDF CONCENTRATIONS IN ASH	51
14	PERCENT REMOVAL OF OTHER ORGANICS	56
15	INLET/OUTLET METAL CONCENTRATIONS	60
16	METAL CONCENTRATIONS IN LIME VERSUS METALS IN HOPPER ASH	63
17	HYDROGEN CHLORIDE CONCENTRATIONS AND REMOVAL EFFICIENCIES	66
18	SULPHUR DIOXIDE CONCENTRATIONS AND REMOVAL EFFICIENCIES	66

ACKNOWLEDGEMENTS

We would like to thank everyone involved in the assessment of the two pilot scale air pollution control technologies for emissions from an incinerator burning municipal solid waste. The program was proposed and initiated by Flakt Canada Ltd. and undertaken in cooperation with Environment Canada under its National Incinerator Testing and Evaluation Program (NITEP). In particular, we are grateful to Mr. Hervé Aubin, Director of Engineering for the Quebec Urban Community, and Montenay Inc., the plant operators, for their cooperation and assistance. Over 30 engineers, chemists and technicians were involved on-site while many dozens more provided laboratory support; without their efforts and dedication this test program would not have been a success.

Since it would be impossible to acknowledge all the individuals involved, special appreciation is extended to the following organizations:

Proponent
- Flakt Canada Ltd.
- Flakt Industri AB (Sweden)

Subcontractors
- IMET, Independent Measurement and Technology Inc.
- Concord Scientific Corp.
- Arthur Gordon Environmental Evaluators Ltd.
- Nova Lab Ltd.
- IEC Beak Consultants Ltd.
- Barringer-Magenta Ltd.

Governments
- Communauté Urbaine de Québec (CUQ)
- Ministère de l'Environnement de Québec (MENVQ)
- Ontario Ministry of the Environment (MOE)
- Supply & Services Canada (DSS)
- Environment Canada (EC)
  - Urban Activities Division (UAD)
  - Pollution Measurement Division (PMD)
  - Analytical Services Division (ASD)
  - Wastewater Technology Centre (WTC)

Funding for this project was provided by Flakt Canada Ltd.; Environment Canada; Energy, Mines and Resources Canada; and the Unsolicited Proposals Program of the Government of Canada. In addition, the Ministry of the Environment of Ontario funded the major portion of an independent quality assurance/quality control program and Environment Quebec provided sampling support and supplies.

Mr. Larry Marentette
Flakt Canada Ltd.
Project Manager

Mr. Raymond Klicius
Environment Canada
Scientific Authority

1 INTRODUCTION

In Canada, the systems for collection and transportation of solid waste created by human activities are, with some possible improvement to enhance opportunities for recycle, generally adequate. In contrast, disposal methods in many areas of Canada continue to be of serious concern. One method that has recently drawn attention is incineration. The increasing costs and complexity of landfilling municipal solid waste, combined with the difficulties of locating new sites, have forced municipalities to seriously consider incineration in energy-from-waste (EFW) facilities. These facilities offer two important benefits: a significant reduction in the volume of waste for disposal, and possible revenue through energy production. Incineration can reduce the volume of waste to be landfilled by up to 90%, extending the life of present landfill sites and reducing the need for new ones. Furthermore, the energy produced by the burning of municipal solid waste provides revenue for the owner and reduces the need for imported fuels.

The concerns that are raised repeatedly with both existing and proposed EFW facilities are the environmental and health effects of emissions. As a consequence of these concerns, and those raised by the Expert Advisory Committee on Dioxins (Ministers of Health and Welfare Canada and Environment Canada), which recognized refuse incineration as a significant controllable input of dioxin into the atmosphere (1), an action plan was developed.

The Action Plan addressed two key committee recommendations: the expansion of efforts to define the optimal design and operating conditions for municipal and industrial incinerators to minimize the production and emissions of dioxins; and the characterization of the best available incineration technologies in Canada through an environmental monitoring program. In response to these two important recommendations, the National Incinerator Testing and Evaluation Program (NITEP) was established by Environment Canada. Through an extensive three-year program, NITEP is investigating three of the most popular incinerator designs, assessing the new add-on pollution control technologies and exploring new incinerator systems. Attempts are being made to correlate combustion conditions with emission of trace organics (dioxins, furans, etc.) and inorganics (metals and acid gases). For incinerators, efforts are being made to define the best "operating window", which will ensure that optimal combustion conditions are maintained to minimize or eliminate emissions of concern. Similarly, various pollution control technologies are being assessed in terms of their design and operating characteristics to further minimize release of contaminants into the atmosphere.

In an attempt to link combustion conditions to emissions, three generic incinerator designs were chosen for study, exemplifying projected trends in technology. The three incinerator designs chosen were a two-stage combustion system, a mass burning system and a prepared refuse burning system. The first candidate studied was the two-stage combustion facility in Parkdale, Prince Edward Island. This work was successfully completed in early 1985 and a summary report was released in September 1985 (2).

The fourth component of NITEP (Incinerator and Pollution Control Technology Assessment) was a field test program developed with Flakt Canada Ltd. to evaluate two proprietary incinerator gas cleaning systems, and is the subject of this summary report.

The literature (3) identifies substantial variation in the quality of emissions from municipal solid waste (MSW) incinerators. Although new modern well-run facilities tend to emit far less than older and less efficiently operated units, the role of the emission control technology applied to these facilities has not been clearly demonstrated. These controls play an important part in maintaining air quality objectives, yet the data base defining their capabilities is limited.

A number of industrial and utility processes have demonstrated that various forms of wet and dry scrubbing devices, usually in series with either fabric filters or electrostatic precipitators, can reduce acid gas and metal emissions. Recently, the scientific community has speculated that organic emissions, such as dioxins, from MSW incinerators may also be reduced by the same type of equipment, provided that appropriate operating conditions are maintained (4,5). Laboratory scale tests recently completed in Denmark appear to substantiate these theories (6). However, there have been no thorough full scale nor large pilot scale tests to evaluate the control of MSW incinerator emissions, particularly trace organics, using such air pollution control systems.

The objectives of the test program developed by Environment Canada and Flakt Canada Ltd. were to evaluate the capabilities of two different control systems to remove particulate, acid gases, heavy metals and particularly trace organics, such as dioxins, and to define the optimum operating conditions to minimize these contaminants.

This report highlights the most significant findings, conclusions and recommendations. Separate volumes containing the main report, methodology, detailed data, a review of an independent quality assurance/quality control program sponsored by the Ontario Ministry of the Environment, and a description of ash leachate work conducted by Environment Canada's Wastewater Technology Centre are available separately from the Industrial Programs Branch at the address provided at the beginning of this report.

2 INCINERATOR DESCRIPTION

The Quebec City Municipal Solid Waste Incinerator Plant, used in this test program, is a mass burning design developed in the early 1970's to burn as-received refuse in a water wall furnace. The plant produces steam using flue gas heat recovery boilers. The incinerator plant is owned by the Quebec Urban Community (QUC) and is located in an industrial area of Quebec City, adjacent to residential and commercial zones. It receives municipal, commercial, and suitable industrial solid waste collected by the Quebec Urban Community, as well as from several other municipalities and private contractors. All of the steam generated by the plant is sold to Reed Paper Ltée. The steam export contract calls for steam to be delivered at a steady (± 7%) flow and specified pressure range. Montenay Inc. operates the plant under a comprehensive operations contract, including the responsibility for all maintenance and servicing.

The principal plant elements, shown on Figure 1, include a refuse storage pit and crane system; four incinerators, each rated at 227 tonnes per day; a common ash storage pit and crane system; and a common stack. Each incinerator consists of a vibrating feeder-hopper, feed chute, drying/burning/burn-out grates, refractory-lined burning zone, water walled partially-lined upper burning zone, a waste heat recovery boiler with superheater and economizer, a two-field electrostatic precipitator, an induced draft fan, and a wet ash quench/removal system.

Two of the incineration units commenced operation in 1974, and all four have been in service since 1975. The units are equipped with Von-Roll designed grates and furnaces, integrated with Dominion Bridge designed boilers. Each of the four units is capable of independent operation and is rated to produce 37 000 kg/h of steam when burning 227 tonnes per day of refuse with a heating value of 13 950 kJ/kg.

The grate is composed of three separate sections, independently driven. The speed of each grate section is manually controlled and the grates are sloped at 15°. The first section is designated as the drying grate, followed by the burning grate and then by the finishing grate. Beneath the grates are hoppers and drop chutes, which receive the siftings passing through the grates, and discharge them into the ash quench tank. The drop chutes are submerged below the ash quench tank water level to seal the furnace against air infiltration.

Primary air is supplied and distributed to five zones located beneath the grates. Air is distributed to the grates so that none reaches the drying grate, approximately 70% reaches the burning grate, and 30% is supplied to the finishing section.

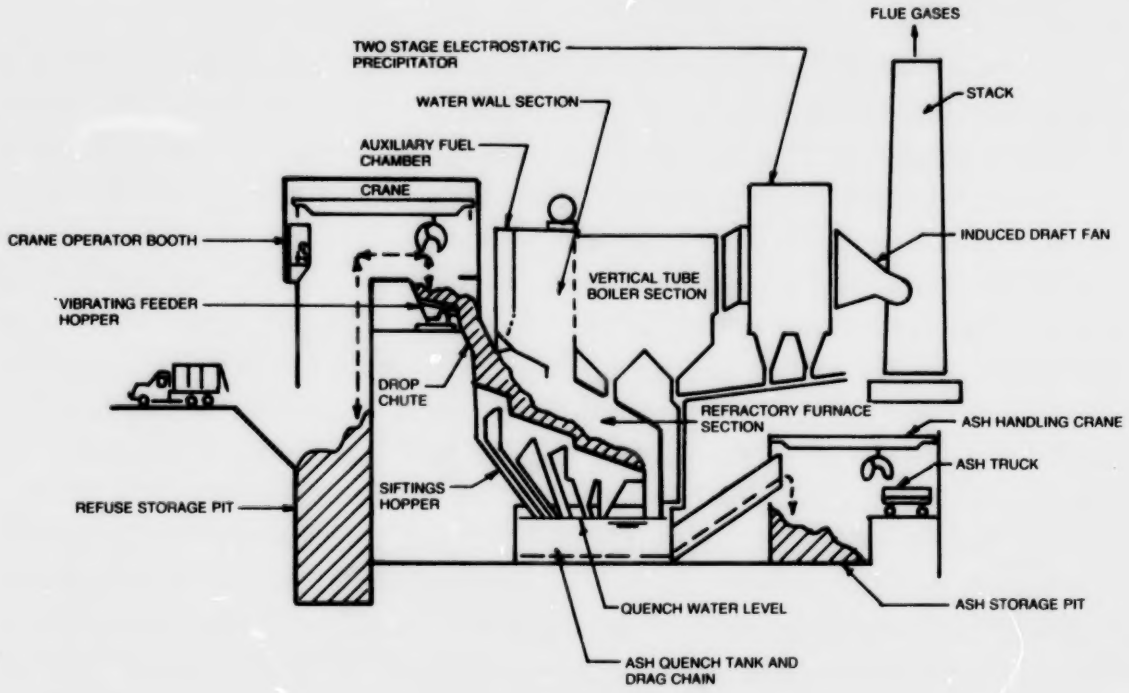


FIGURE 1 QUEBEC INCINERATOR SCHEMATIC CROSS-SECTION

The total primary air is automatically paced by steam flow (i.e., air flow is increased on lower than set point steam production and decreased on higher than set point steam production). Secondary air is introduced at a manually set fixed rate through 20 nozzles in the water-cooled arch. Both primary and secondary air are drawn from the refuse pit area.

Flue gas exiting from the boiler sections passes into a two-field electrostatic precipitator via a short transition flue containing a perforated distribution plate. The flue gases leaving the precipitator are drawn through an induced draft fan and discharged into a single flue stack, common to all four incinerators.

The plant control panel displays the status of the operation, and includes instrumentation and controls for the common services, such as total plant steam, total steam exported, as well as oxygen recorders and opacity meters, for all the incinerators. Four separate panels display the status of operation and control for each unit.

Ash residue from the incinerator, including grate siftings and unburned material discharged off the end of the finishing grate, is discharged into a water-filled

quench tank below. Fly ash from the evaporator/economizer hopper and from the precipitator hoppers is transferred by a bulk flow conveyor to the quench tank. Ash that settles to the bottom of the quench tank is transferred along the bottom by a drag chain conveyor up an incline from which some water drains back to the quench tank. The ash falls off the end of the incline into the ash storage pit. The ash is transferred by an overhead crane to an ash transport truck for disposal. A more thorough description of the incinerator and its operation is presented in Volume II, the detailed program report.

Quebec's no. 3 incinerator was used for the test program. No modifications were made except to install a flue-gas take-off duct arrangement. This duct was used to extract a slip stream of raw gas from the incinerator prior to its entry into the existing electrostatic precipitator used for air pollution control.

3 PILOT PLANT DESCRIPTION

3.1 Scrubbing Processes

The design of the Flakt Canada Ltd. pilot plant was based on scrubbing technology developed for flue gas desulphurization (FGD), commonly used in the utility industry for sulphur dioxide removal. Three scrubbing concepts can be used to clean flue gas.

Wet scrubbing is the conventional process of contacting the hot flue gas with a solution of water and some dissolved chemical, typically in a cylindrical vessel. The products from this process are an effluent stream of spent liquid from the bottom of the vessel and a clean humid flue gas out the top of the vessel. Because of the inherent disadvantages of having to dispose of a liquid effluent and adverse experiences in Europe, this type of scrubbing system was not evaluated in this study.

Dry scrubbing involves partial cooling of the hot flue gas and then contact with a dry chemical powder in a vessel. For sulphur dioxide removal, a dry alkaline chemical such as hydrated lime, reacts with the sulphur dioxide in the flue gas. The reaction products are dry and can be easily collected with the fly ash in a device such as a fabric filter or electrostatic precipitator. Two advantages of dry scrubbing are the absence of a liquid effluent and reduced equipment corrosion. As further discussed below, dry scrubbing was one of the technologies evaluated in this study. The vessel used to react powdered lime with flue gas is called the "dry scrubber" in this report.

Wet-dry scrubbing is a combination of the above scrubbing processes in which the hot flue gas is contacted by a solution (slurry) of water and some dissolved chemical, such as hydrated lime, in a vessel. The main difference is that the proportion of liquid (water in slurry) to flue gas is carefully controlled to ensure that all the water is totally evaporated and the dissolved lime goes into suspension as fine particulate in the gas. As in the above dry scrubber process, the reaction products are all dry leaving the vessel and the particulates are subsequently removed in a fabric filter or electrostatic precipitator. The vessel used to react lime slurry with flue gas is called the "wet-dry scrubber" in this report.

To partially cool the flue gas in the dry scrubbing process (to protect the fabric filter bag material from high temperature exposure), the wet-dry scrubber vessel was used as a gas cooler or gas conditioner. In place of a slurry, water was added to the vessel, which lowered the gas temperature prior to entering the dry scrubber vessel.

3.2 Plant Design

The considerable experience gained by Flakt's international companies with gas cleaning systems in Europe and Japan was instrumental in the design of the pilot plant. Each component of the pilot plant used in the test program was selected from actual operating equipment, scaled down to a size that allowed for flexibility in addressing a wide range of operating conditions while maintaining reasonable costs to the test program.

A critical component used in selecting the size of the pilot plant was the carbide tip of the slurry spray nozzle in the wet-dry scrubber. The use of a single nozzle tip in the wet-dry scrubber determined the slurry rate and, accordingly, the flue gas flow rate capacity of the scrubber. All other ancillary equipment (e.g., fan, ducting, dry reactor, etc.) was sized based on the gas flow. The facility constructed is a large scale pilot plant, of sufficient size to demonstrate operations and to provide results representative of a full-scale facility.

Flakt Canada's engineering department designed all equipment items, prepared equipment specifications and purchased all components. In addition, Flakt personnel supervised all facets of field installation and commissioned start-up of the facilities.

3.3 Pilot Plant Components

The principal components of the Flakt pilot plant (shown in Figures 2 and 3) are as follows:

- A flue gas slip stream take-off duct (with 8 inlet nozzles) from the electrostatic precipitator inlet of incinerator unit no. 3, to obtain a representative sample of flue gas to the pilot plant (see Figure 3).
- A wet-dry scrubber - Flakt's DRY-PAC design (also used as gas cooler) with slurry spray nozzle and bottom screw conveyor.
- A dry scrubber - Flakt's DAS design, with single dry lime injection nozzle and internal cyclone integral with the scrubber at the entrance.
- A pulse-jet fabric filter - Flakt's OPTIPULSE design, using high temperature Teflon bags as the filtering media and an air-to-cloth ratio of 4.4 ACFM/sq. ft. (80 Am^3/h per m^2).
- An induced draft (I.D.) fan with flow venturi.
- A stack.

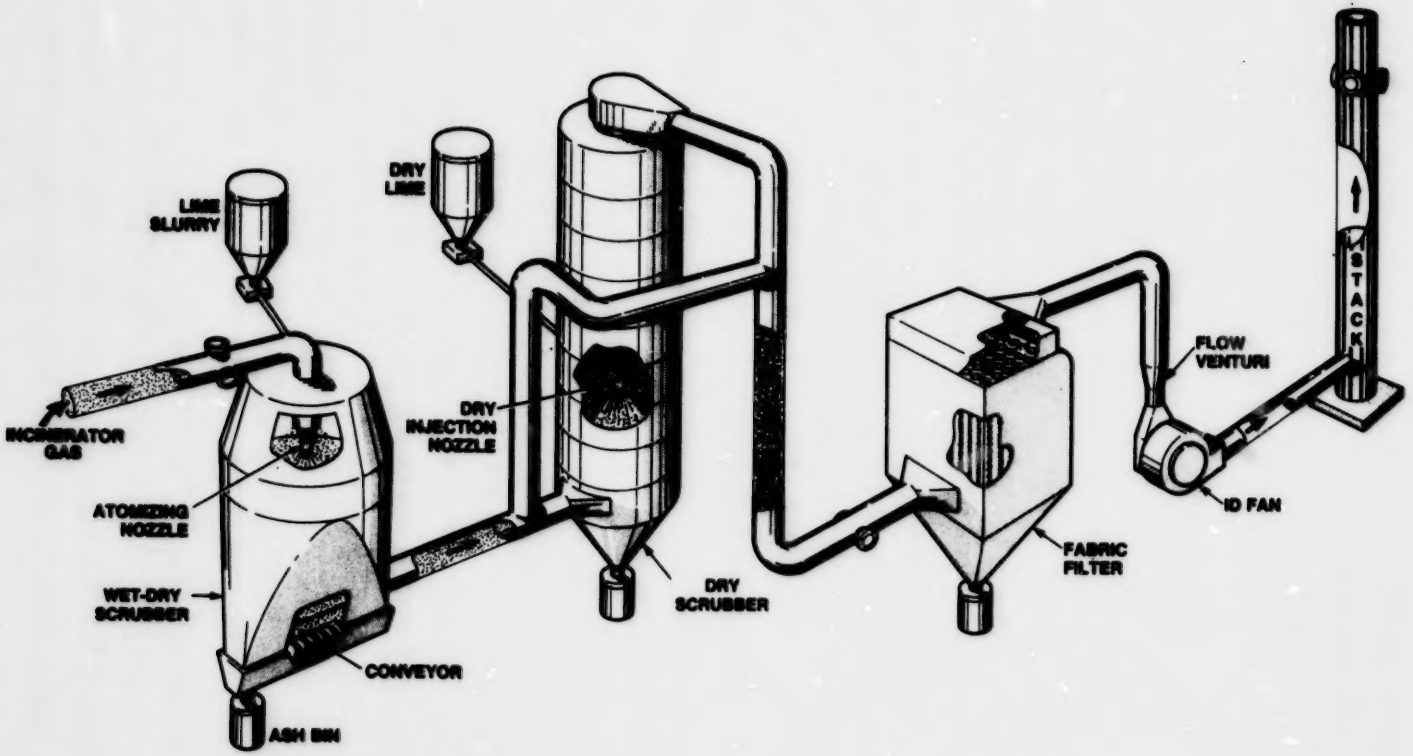


FIGURE 2 FLAKT'S PILOT PLANT MAIN EQUIPMENT COMPONENTS

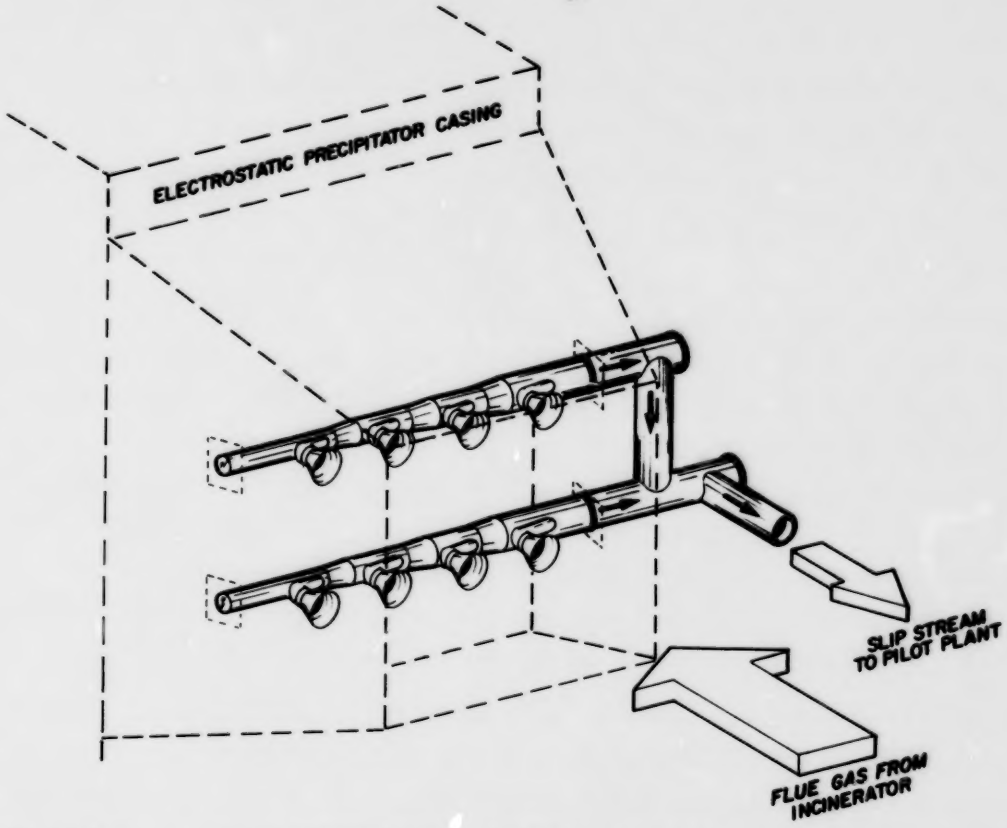


FIGURE 3 INCINERATOR GAS SLIP STREAM TAKE-OFF ARRANGEMENT

Ancillary equipment includes by-pass ducts across the dry scrubber and fabric filter; removable/portable ash hopper drums on each of the three vessels; flue gas duct isolating dampers and I.D. fan flow control damper; two lime slurry variable-speed pumps with associated slurry mix tanks, agitators, controls and hose; a venturi/eductor dry lime feeding system with variable-speed control; dry lime silo; and a fabric filter with pulse pressure, pulse duration and pulse timer control system.

Certain proprietary aspects of the design of Flakt's scrubbers and fabric filter distinguish this equipment and the efficiencies achieved from similar air pollution control equipment from other suppliers.

The pilot plant operates in one of two modes, as discussed below.

3.3.1 Dry System. In the dry system (see Figure 4), hot flue gas from the incinerator enters at 255-270°C into the wet-dry scrubber (now in the role of a gas cooler) and is cooled to about 110 - 140°C with a water spray. The gas then enters the bottom of the dry scrubber vessel tangentially into an internal cyclone, where large particles of

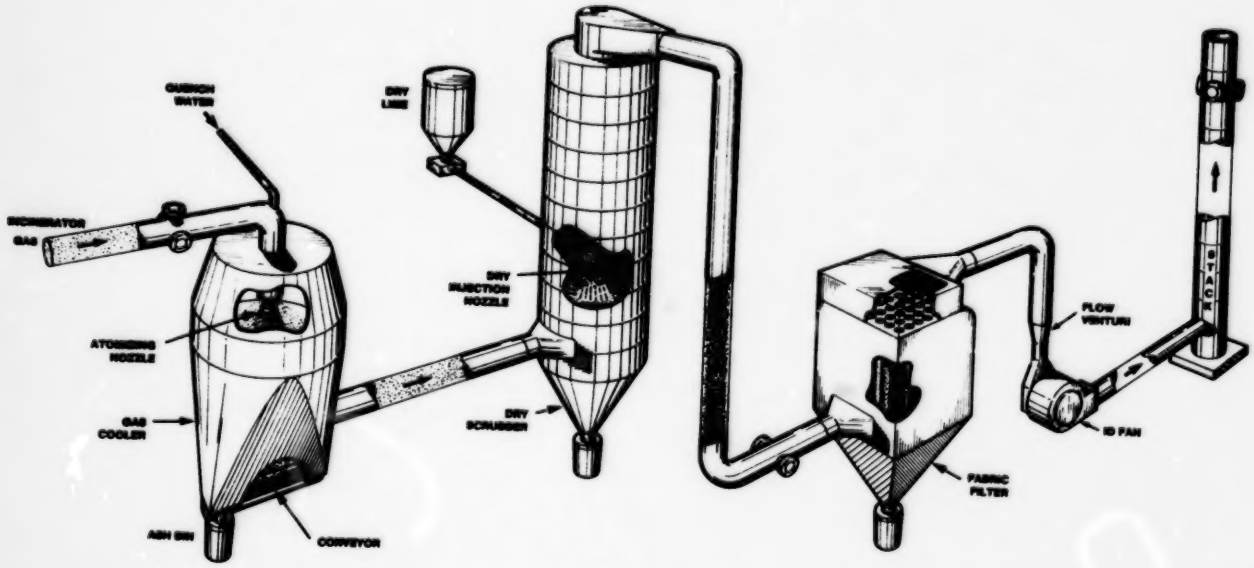


FIGURE 4 FLAKT'S DRY SYSTEM

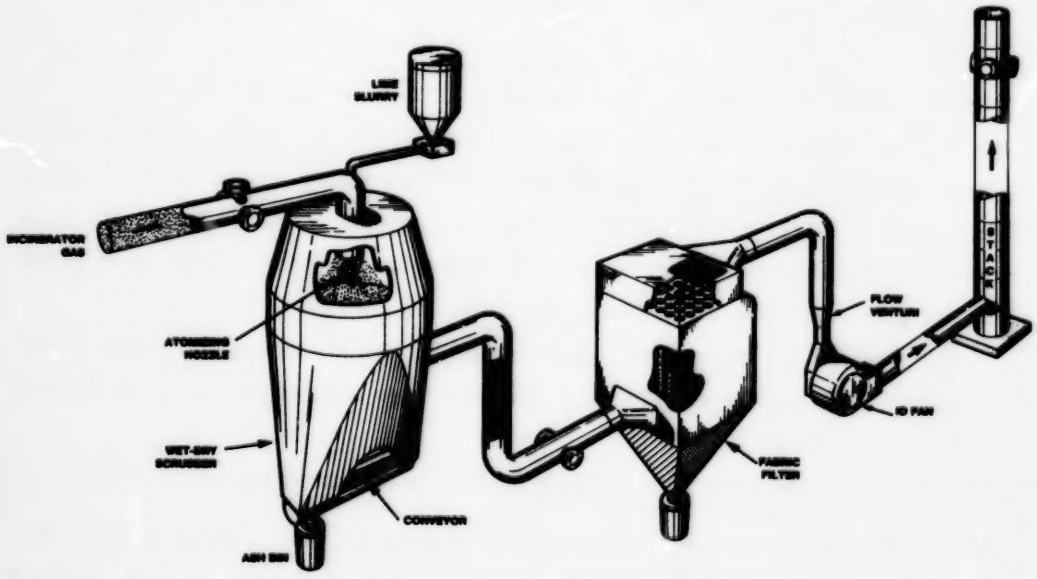


FIGURE 5 FLAKT'S WET-DRY SYSTEM

entrained fly ash are removed. The flue gas is then chemically treated with a dry hydrated lime powder, which is injected with compressed air through a single nozzle directed downwards into the gas stream. The cooled and conditioned flue gas, with entrained dry lime reaction products, flows to the fabric filter which serves as the final stage of pollutant removal.

3.3.2 Wet-Dry System. In the wet-dry system (see Figure 5), hot flue gas from the incinerator enters the top of the wet-dry scrubber at 255-270°C where it is intimately mixed and cooled with a finely atomized lime slurry spray. The mixing occurs in an area of extreme turbulence produced by an inlet dispenser baffle plate/venturi arrangement. The quenched (110°C -140°C) and chemically conditioned flue gas then enters the fabric filter for final treatment.

Both systems described can operate with fabric filter "ash" recirculation. This ash contains some unreacted hydrated lime which is mixed with fresh lime in either slurry or dry form before being reinjected into the associated scrubber.

3.3.3 Fabric Filter. The fabric filter is a one compartment baghouse containing 72 bags arranged in 6 rows of 12 bags each. The bag material is Teflon with Gortex scrim. It is chemically inert to acid gases and has a maximum operating temperature of 250°C. The bags are supported on cylindrical wire cages. Particulate collection occurs on the outside of the bags with the cleaned flue gas moving through the bags and exiting from the cell plate at the top of the fabric filter compartment. The bags are cleaned using Flakt's OPTIPULSE low pressure air pulses delivered through timer controlled pulse valves to individual bag row manifold pipes. The air is directed through discharge nozzles at the cell plate level down into the top of each bag.

3.3.4 Process Control. The pilot plant process control system was relatively uncomplicated. A key control parameter for the process was the temperature at which the fabric filter was maintained during the tests (typically 110°C to 140°C). Temperature control was accomplished by adjusting either the rate of slurry into the wet-dry system or the rate of water spray into the dry system.

The flow of flue gases through the system was controlled by adjusting the damper at the inlet of the induced draft fan. To ensure constant flows were maintained during the tests, the pressure drop across a venturi upstream of the I.D. fan was monitored frequently.

4 SAMPLING AND ANALYTICAL PROTOCOLS

4.1 Test Program Considerations

The purpose of this study was to address a number of environmental interests of both Flakt Canada and Environment Canada, which required extensive planning to develop a program that would satisfy the objectives of both parties. The emissions of interest were from the following groups: acid gases, particulate, mercury, heavy metals and trace organics. As with a previous NITEP study at the Parkdale, Prince Edward Island incinerator, the field tests were divided into two parts: firstly, characterization -- to test a wide range of operating conditions with limited emissions monitoring; and secondly, performance -- to conduct extensive testing for all emissions of concern.

In addition, the characterization tests provided the program coordinators with operating experience, an appreciation of equipment limitations and, subsequently, the basis for selecting those operating conditions that merited detailed performance testing.

Three sampling locations were selected to determine removal efficiencies:

- **Inlet** - before pilot plant. This location was required to obtain data on untreated raw gases from the incinerator.
- **Midpoint** - after scrubbers but before fabric filter. Testing at this location was considered important to examine the possible enhancement in collection efficiency across the fabric filter. A number of well-documented studies (7,8) have indicated that lime cake on the fabric filter bags can enhance hydrogen chloride and sulphur dioxide removal, as well as metal removal but organic emissions have not been well documented.
- **Outlet** - stack downstream of the fabric filter. This location was sampled to determine how much of the pollutants were removed from the systems tested.

In addition to the gaseous samples taken at these three locations, samples of all ash discharged by the scrubbers and the fabric filter were collected and analyzed for metals and trace organics during the performance tests.

During performance testing, 10 manual sampling trains and 13 continuous gas monitors were operated simultaneously, involving a team of 33 engineers, chemists and technicians. This section of the report provides a brief outline of the sampling methods used and the organic and inorganic analytical methods employed.

4.2 Manual Sampling

Four types of manual sampling trains were used during the performance test series:

- particulates/metals/hydrogen chloride (HCl) - MPHCl,
- mercury,
- organics,
- hydrogen chloride (HCl).

With the exception of a midget impinger train dedicated to collecting hydrogen chloride samples, all other manual sampling methods were based on the U.S. Environmental Protection Agency Method 5 train. In general, each train consisted of the following components:

- a goose-neck nozzle (front-half),
- a glass-lined heated probe (front-half),
- a heated cyclone and filter assembly (front-half),
- a series of impingers or cartridges, cooled by an ice bath (back-half), containing pollutant-specific scrubbing agents and,
- a sampling console.

Particulates in the gas stream were collected by a cyclone and a glass fibre filter, both contained in a heated enclosure. Following particulate removal, the sample gases were then passed through an impinger train to remove the gaseous components. In the particulates/metals/HCl train, gaseous HCl and metals were scrubbed by a series of water and aqua regia-filled impingers. In the mercury train, mercury was scrubbed by two impingers containing potassium permanganate. In the organics train, gaseous organics were trapped in a resin tube containing Amberlite XAD-2 and an ethylene glycol-filled impinger. A schematic of these three sampling trains is shown in Figure 6.

Sampling duration for each test (except the short term HCl trains) was four hours. All trains were operated simultaneously. The stack gas for each train was collected through two ports located at 90° to each other and involved isokinetic sampling at six points along each traverse. Sampling at each point was 10 minutes with readings recorded every five minutes. Each traverse was repeated twice. Leak checks were conducted at the beginning and at the end of each traverse or whenever a train connection was opened.

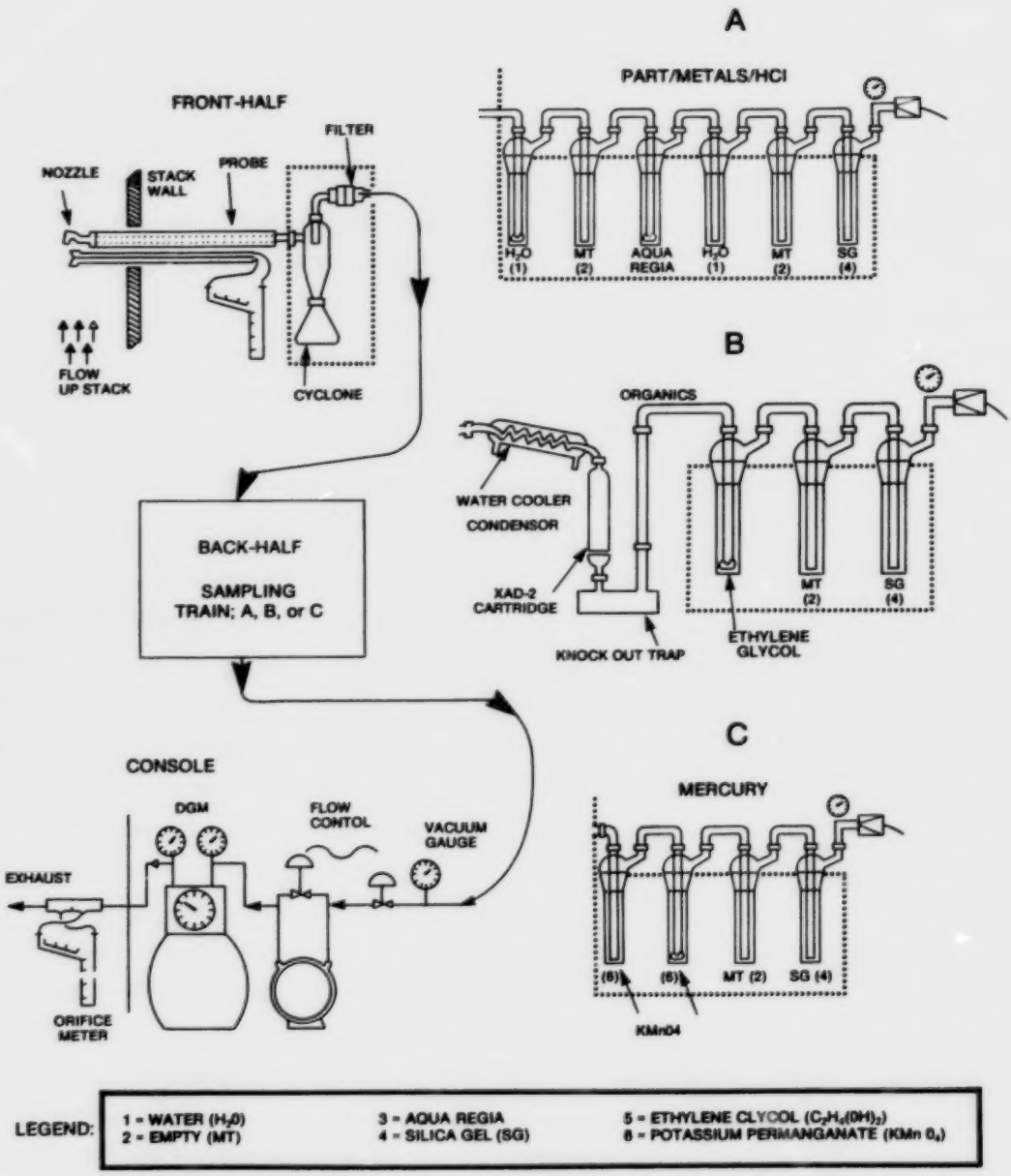


FIGURE 6 SCHEMATIC OF SAMPLING TRAINS

In the case of the dedicated hydrogen chloride trains, gaseous hydrogen chloride was removed in two water-filled midget impingers. Particulate matter was removed by a glass wool plug at the entrance of a heated probe. Sampling rate was constant and a run consisted of either a 15-minute or a 30-minute sampling duration. Leak checks were also performed on this train.

In addition to the regular organic sampling trains, a blank train was assembled for every three tests. The blank trains were treated in the same manner as the organic sampling trains except that no stack gases were sampled. However, a volume of ambient air, equal to that drawn during the pre- and post-traverse leak checks, was drawn through the blank train. Essentially, the blank trains served as a check for background levels of organics.

Following the completion of sampling, all trains were brought to the three on-site laboratories for sample recovery. All three organic trains were recovered in a dedicated laboratory by the Analytical Services Division of Environment Canada. Flakt Canada Ltd. was responsible for recovery of the particulates/metals/hydrogen chloride and mercury train at the inlet whereas the Pollution Measurement Division of Environment Canada recovered these trains from the outlet site.

Sample recovery for the particulates/metals/hydrogen chloride train entailed the quantitative recovery of particulates, taking an aliquot of the first impinger solution for chloride analysis, and recovery of the aqua regia and water impinger solutions for metals analysis.

In the mercury train, mercury in the particulate form was recovered by washing the front-half components with dichromate and immersing the loaded filter into this recovered solution. Recovery of the impingers involved the reduction of the permanganate solutions with hydroxylamine hydrochloride followed by preservation of the contents with a dichromate solution. The salient feature of the mercury method was the use of preserving agents to eliminate any mercury losses from the storage containers.

Recovery of the organic trains involved brushing and rinsing most of the train glassware with acetone and hexane. Loaded filters were folded and placed in pre-cleaned aluminum foil, which was then stored in a pre-cleaned glass petri dish. Amberlite resin tubes were capped and re-wrapped in aluminum foil. All liquid samples were stored in pre-cleaned amber bottles (with pre-cleaned teflon lid liners) to prevent photodegradation of the samples. Finally, following recovery, all samples were refrigerated. Likewise, samples were stored in insulated coolers during transport to the main laboratory each day, immediately after recovery of the samples in the field laboratory.

Samples were recovered from the dedicated hydrogen chloride train by combining the first two impinger solutions with a deionized water rinse of the glassware downstream of the probe.

All train glassware and sample storage containers were cleaned using specified procedures prior to the program. The effectiveness of these procedures was verified by taking a proof rinse of the glassware and containers with the rinsing reagent used in the recovery procedure. No glassware or containers were used unless they met the acceptance criteria. Glassware used in the organic trains had to be proofed before re-use and all containers used to hold the proof rinses were individually proofed.

4.3 Continuous Gas Monitors

Continuous real-time instrumentation was used to measure simultaneously the concentrations of the gaseous constituents listed below:

Constituent	Inlet	Mid-Point	Outlet
Hydrogen Chloride	Flakt	Flakt	EC
Sulphur Dioxide	Flakt	Flakt	EC
Oxygen	Flakt		EC
Total Hydrocarbons	EC		EC
Water		Flakt	
Carbon Dioxide			EC
Carbon Monoxide			EC

EC = Environment Canada; Flakt = Flakt Canada Ltd.

These 13 instruments, representing 10 different analyzer types and 8 different gas sample conditioning system combinations, are described in Table 1. Some analyzers were tested in the laboratory for reproducibility, zero and span drift and linearity before use in the field. Once on-site, most of the instruments operated over the entire test period and generated valid data. Exceptions were the total hydrocarbon (THC) analyzer at the inlet, which was used for only four tests, and the hydrogen chloride analyzer at the same location, which operated satisfactorily only during the last four runs.

The hydrogen chloride analyzer located at the mid-point operated on a wet basis -- as did the moisture analyzer. As all other instruments operated on a dry basis, two basic sample extraction and conditioning systems were required. In general,

TABLE 1 DESCRIPTION OF ANALYZERS FOR CONTINUOUS GAS MONITORING

System No.	Location	Agency	Gas	Basis	Analyzer Data		
					Model	Principle	Range
1	Inlet	Flakt	SO_2	Dry	WRD 721 A	NDUV	0-250 ppm
			O_2	Dry	Servomex 570 A	Para	0-25%
2		Flakt	HCl*	Dry	Teco 15	GFC	0-1000 ppm
3		EC	THCc**	Dry	Ratfisch RS 5	FID	0-30 ppm
4	Mid-point	Flakt	HCl*	Wet	Bodenseewerk 677	GFC	0-209 ppm
			H_2O		Bodenseewerk 657	NDIR	0-100%
5		Flakt	SO_2	Dry	WRD 721 A	NDUV	0-250 ppm
6		EC	THCh**	Wet	Ratfisch RS 5	FID	0-30 ppm
7	Outlet	EC	HCl	Dry	Teco 15	GFC	0-200 ppm
8		EC	SO_2	Dry	WRD 721 A	NDUV	0-200 ppm
			CO		Bendix 8501-5BA	NDIR	0-250 ppm
			CO_2		Anarad AR-421	NDIR	0-20%
			O_2		Teledyne 320/P4	FC	0-25%
			THCc		Beckman 400	FID	0-20 ppm

* Operated during a portion of performance test series.
** Instrument operated at inlet and outlet.

NDUV - Non-dispersive Ultraviolet
GFC - Gas Filter Correlation
Para - Paramagnetic
NDIR - Non-dispersive Infrared
FID - Flame Ionization Detector
FC - Fuel Cell

h = hot
c = cold

representative gas samples were extracted from the source. Particulate matter was removed with further treatment to remove uncombined moisture, depending upon the demands of the analyzer. The instruments were calibrated using commercially available span gases which had been verified by the best available reference methods. Calibration gases were also injected on-site at the analyzer inlet, conditioning system inlet and at the entrance to the heated sampling line in order to obtain an overall system check and to identify possible losses within the system.

The data logging system for the continuous monitors utilized a microprocessing real-time data capture system. Chart recorders were used as standby devices in the event of a failure of the microprocessor system and to provide a means to observe the data for trends. Additionally, the recorder charts provided a hard copy of instrument calibration data for quality assurance/quality control (QA/QC).

Data scan frequency was set at 20 seconds with data from each scan displayed on the computer monitor for immediate review. Five and 15 minute averages were calculated from the 20 second scans and outputted to a printer. The data were immediately scrutinized for accuracy and changes made where necessary. After each 2.5-hour period of operation, 15-minute averages of these data were entered into an IBM-PC, which was used for the storage of all the data collected during the survey.

4.4 Process Data and Ash Samples

All incinerator and pilot plant operating data were recorded at specific intervals to accurately characterize the operating condition of both the incinerator and the pilot plant.

Process ashes were collected from the various vessel hoppers. During the dry injection mode, ash was collected from the conditioning tower (wet-dry scrubber), dry scrubber and fabric filter hoppers. In the wet mode, ash was collected from the wet-dry scrubber and the fabric filter hoppers. Sub-samples of each of the ashes were collected and sent for laboratory analyses for heavy metals and trace organics.

4.5 Analytical Procedures

All organic analyses were conducted at Environment Canada's River Road Environmental Technology Centre (RRETC) in Ottawa by the Analytical Services Division (ASD). In addition, ASD completed all chloride analyses for hydrogen chloride content and mercury analyses for the mercury sampling trains. All other metals were analyzed by IEC Beak, including mercury in the process ashes. The various analytical procedures are briefly outlined below.

4.5.1 Organic Analysis. A major objective of the Flakt pilot plant tests was to define stack emission and process ash levels of six classes of organic compounds under a variety of operating conditions. The following classes of compounds were targeted for analysis: polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), polychlorinated biphenyls (PCB), chlorinated benzenes (CB), chlorinated phenols (CP), and polycyclic aromatic hydrocarbons (PAH).

The four basic steps in the processing and analysis of all samples were:

1) solvent extraction of organic constituents from the sample matrix;
2) clean up of the raw extract to remove some of the co-extracted non-target organics, and to separate target organics into four fractions for class-specific analysis;
3) instrumental analysis of each fraction; and
4) data interpretation and quantitation of target organics.

Figure 7 summarizes sample processing and analysis in schematic form. The raw extract for each sample was split in half. The two halves were subjected to different cleanup protocols, each cleanup yielding two fractions for analysis. One cleanup protocol separated chlorobenzenes and PCBs from PCDD/PCDF, while the other cleanup isolated chlorophenols from co-extracted organics, including PAH. Typical final volumes for each of the four fractions are indicated on the schematic.

All fractions were analyzed by gas chromatography/mass spectrometry (GC/MS). Gas chromatography is a technique by which individual components in a complex mixture of target and non-target organics can be separated from each other. The mass spectrometer serves as a detector for the individual sample components. This powerful tool can be programmed to respond selectively to target organics based on their known molecular masses and characteristic molecular fragmentation patterns.

A large volume of semi-processed GC/MS data was generated for each sample analyzed. Final interpretation of all data was performed manually to screen out any data that did not satisfy all of the established criteria for target compound identification.

For dioxins and furans in flue gas samples, "N.D." or "Not Detected" in the tables of results is defined as follows:

- 0.2 ng per analyte peak per sample for T4CDD, T4CDF, P5CDF, H6CDF
- 0.4 ng per analyte peak per sample for P5CDD, H6CDD, H7CDF, O8CDF
- 0.6 ng per analyte peak per sample for H7CDD, O8CDD

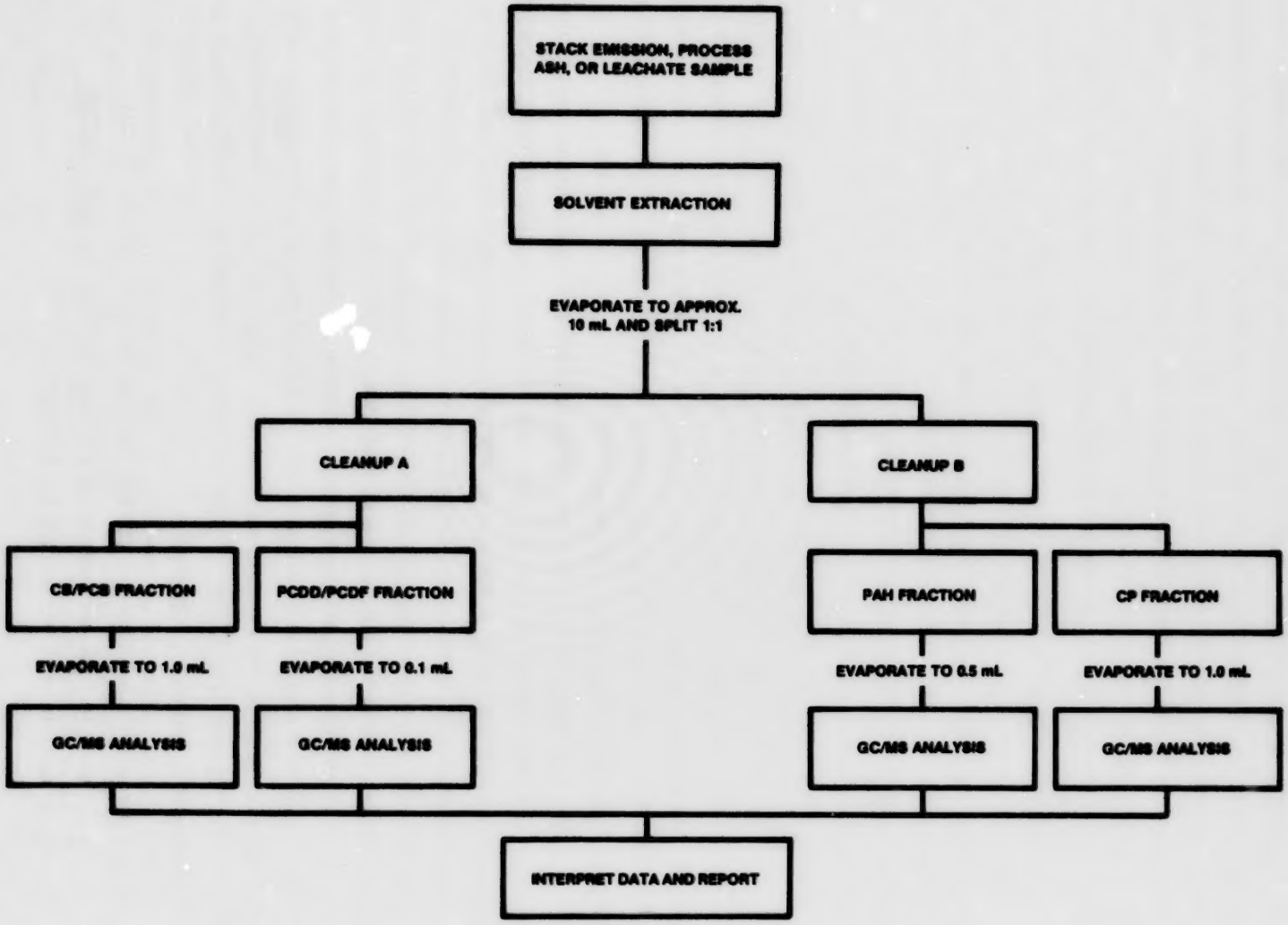


FIGURE 7 SCHEMATIC OF ORGANIC SAMPLE PROCESSING AND ANALYSIS

For dioxins and furans in ash samples, the detection limits are two times the above values.

For other organics, "N.D." or "Not Detected" in the tables of results is defined as follows:

- 2 ng per congener per sample for chlorobenzenes
- 2-10 ng per sample for polychlorinated biphenyls
- 30 ng per congener per sample for chlorophenols
- 10 ng per sample for each polycyclic aromatic hydrocarbon

All dioxin and furan data are recovery-corrected. Data for other organics are not recovery-corrected. Recovery factors are tabulated in the detailed data report, available separately.

4.5.2 Metals Analyses. Train component samples were prepared in a manner compatible with an aqueous or solid matrix. Water samples were either evaporated or digested. Solid samples and filters were digested with aqua regia.

The acetone probe wash was evaporated to dryness to measure total particulate, then the solids were digested with aqua regia for elemental analysis. Mercury was determined directly on this digest after treatment with hydroxylamine reductant. Arsenic and antimony were prereduced with hydrochloric acid and potassium iodide before hydride formation.

The filter sample was digested whole with aqua regia and analysed similarly as the probe wash solids.

The dust ash and lime samples were digested with aqua regia and analysed like the probe wash solids.

Impinger contents and water samples were either concentrated by a factor of two or digested. Mercury was determined after digestion with sulphuric-nitric acids and potassium permanganate-persulphate.

Train samples were digested with hydrochloric acid. The digests were then treated with hydrogen peroxide and mercury reductant prior to analysis.

Elements were analysed using direct current plasma emission spectrometry (DCP) with these exceptions: Mercury was determined by measuring the mercury vapour concentration by flameless atomic absorption spectrometry (FAA). Arsenic, antimony, bismuth, selenium and tellurium were determined by formation of their metal hydrides and analysis by flameless atomic absorption spectrometry.

All analyses were carried out following documented procedures and adhering to standard laboratory quality control practices. Some DCP elements were verified by flame AA.

4.5.3 Chloride Analysis. Chlorides were analyzed by means of ion chromatography. In this technique, chlorides in solution are separated from other ions on an ion exchange column. Cations in the sample solution are exchanged on a second (suppressor) column. The conductivity of the resulting acids is measured by a micro-conductivity cell and chloride concentrations are determined by comparison with a previously prepared calibration curve.

4.5.4 Leachability Tests. To increase the data base for the leachability of organic and inorganic compounds present in ashes from municipal solid waste incineration processes, each of the three types of ashes collected by the pilot plant facilities was tested for leachability of PCDD, PCDF, CB, PCB, PAH, CP and various selected metals. Bench scale leaching tests using a 20:1 liquid-to-solid ratio distilled water leach, as well as sequential chemical extraction leaching tests, were completed. These results will be available shortly and will be issued in a separate report.

4.6 Quality Assurance and Quality Control

Due both to the importance of the NITEP test work and the extensive amount of sampling and data gathering, an independent, third-party quality assurance and quality control (QA/QC) program was established in addition to the standard QA/QC that is part of the sampling and analytical requirements.

The objectives of the QA/QC program were as follows:

- to produce data with the maximum possible accuracy, precision, completeness, representativeness and comparability through the design of QA/QC procedures which ensure that all components of the program are carried out in a manner which minimizes all negative effects on data quality; and
- to quantify the levels of acuracy, precision, completeness, representativeness and comparability of data collected during the study.

To meet these QA objectives, a rigorous and comprehensive QA/QC program was designed and implemented during the preparation phase. The program ensured that the data reported and analyzed are complete, and it documented the measure of precision and accuracy of the analytical results. A number of QA/QC procedures were incorporated

into the standard operating procedures and distributed to project personnel in the form of a manual prior to commencement of the field testing. This manual served as a QA reference for project personnel by documenting the specific QA procedures, schedules, responsibilities, reporting mechanisms, operating procedures, etc. that should be followed for each phase of the program, namely mobilization, characterization, performance and laboratory analysis.

Overall, the manual train and continuous sampling was very successful, considering the number of sampling trains and gas monitors that were run simultaneously. Out of 91 manual train runs, operated for four-hour periods during the performance test series, only five train runs were invalidated. One was the MPHCl run at the inlet for performance test number 4 (i.e., PT-4), and another was the MPHCl run at the outlet for PT-13. Three other runs were invalidated during the first performance test (PT-1): the Hg and MPHCl runs at the inlet and the organic run at the midpoint. Consequently, PT-1 was designated a preliminary test run and this test run was repeated during PT-11.

To supplement the HCl continuous monitors, 186 midget impinger HCL runs (15-30 minutes) were conducted. The results from the supplementary manual HCl runs conducted at the midpoint are not reported, since it was considered that the lime-rich dust collected on the glass wool was scrubbing HCl from the sample gas. In its place, HCl continuous monitoring data have been used.

In the case of the continuous analyzers, only the data from the HCl inlet monitor for runs PT-1 to PT-7 were invalidated. In their place, manual train data for HCl at the inlet were used.

Samples collected were analyzed for organics, heavy metals, mercury and chloride content. The types of samples analyzed included train samples (filters, resins, impinger solutions), fabric filter dust, dry scrubber product, wet-dry scrubber product and lime samples. To quantify the analytical precision and accuracy and to assess the reliability of the analytical data, an external laboratory QA/QC program was also initiated.

This laboratory QA/QC program involved submitting a number of split samples, analytical sample extracts, triplicate samples and standard reference materials to both the main laboratory and one other laboratory that was designated to perform QA analysis.

To monitor the analytical performance on every sample for every organic parameter group, surrogate standards were added to the samples prior to conducting the entire analytical procedure. The data on surrogate concentrations were used to calculate

the recovery of the surrogate compounds and thus provide a measure of accuracy of the sample preparation and analysis procedure.

Two National Bureau of Standards (NBS) Standard Reference Materials (SRM) were submitted blind to the laboratories for analysis of organics (SRM 16949) and heavy metals (SRM 1648). This procedure provided a measure of the accuracy of the analysis on a homogenous sample through comparison with the certified data.

In addition, five fabric filter dust samples were analyzed in triplicate for organics and heavy metals to quantify the precision of the analysis by the main laboratory and QA laboratory.

The results of the laboratory comparison QA program can be summarized as follows:

For metals - Good correlations were found between laboratories for a majority of the elements analyzed, and the intra-laboratory variations were minimal for most elements. As expected, at lower concentrations more variation existed in the data. A consistent low bias of the data is evident in the QA laboratory's results.

For organics - Correlations between the two laboratories were good with the exception of PCB and CB. Extemely low concentrations of PCB resulted in large intra-laboratory variations in the analytical results for both laboratories. The QA laboratory also experienced CB contamination problems which produced poor intra laboratory results for the QA laboratory.

Overall, both the metals and the organics data are considered to be representative of the emissions occurring at the time of sampling.

5 TEST PROGRAM DESCRIPTION

As previously discussed, the test program was divided into two parts: characterization testing, and performance testing. The objective of characterization testing was to screen a number of operating modes so that a select few performance test conditions could be identified, using a limited amount of testing.

5.1 Characterization Tests

One "pretest" or familiarization day was required before the 13 characterization tests (CTs) were begun. The testing was divided into the dry mode operation and wet-dry mode operation, as shown in Table 2.

TABLE 2 SUMMARY OF CHARACTERIZATION TEST CONDITIONS

Operating Mode	Temperature After Cooling		Lime Feed Rate	Test No.
	Target °C	Actual °C		
Dry System				
Normal Temp. Operation	140	145	Normal	11
	140	151	High	4
	140	152	High (+ Recycle)	5
	140	151	Very high	3
High Temp. Operation	>200	222	Very high	2
Low Temp. Operation	125	133	Normal (+ Recycle)	12
Wet-Dry System				
Normal Temp. Operation	150	156	Normal	6, 10
	150	158	High	8
	150	158	High (+ Recycle)	9
	150	156	Very high	7
Low Temp. Operation	135	141	Normal	13
	135	144	Normal (+ Recycle)	14

Both operating systems were tested over a range of operating temperatures and hydrated lime feed rates - these being the two most important independent variables. The other operating variables of the pilot plant were kept as constant as possible during the tests. The type of data collected by the continuous gas monitors, manual sampling trains and plant instrumentation are summarized in Figure 8. All the data obtained were entered into a personal computer and then reduced to summary tables and graphs to

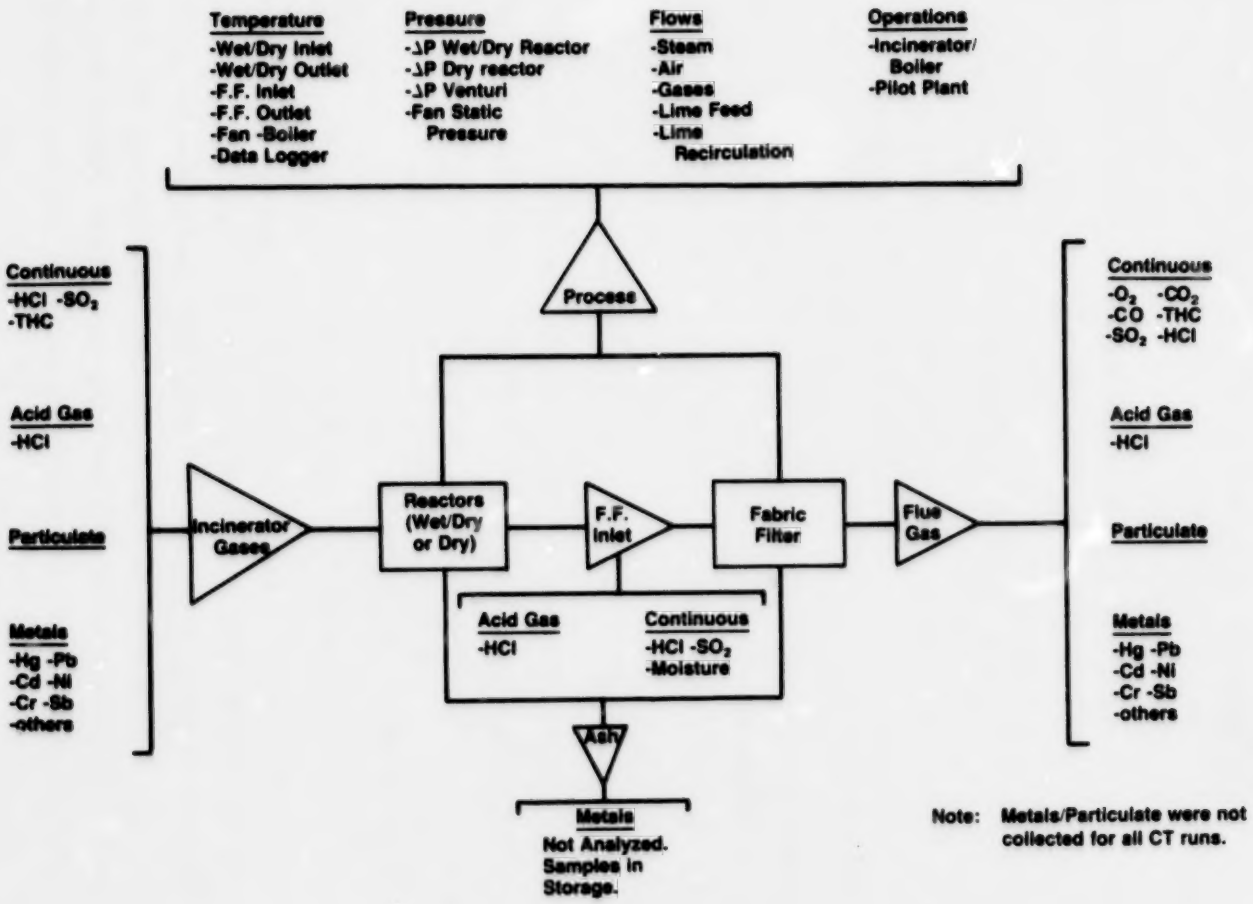


FIGURE 8 PARAMETERS MEASURED DURING CHARACTERIZATION TESTING

facilitate review of the results. These results were made available to the field managers on the following morning to assess the adequacy of the previous day's test results.

The "Normal Temperature" conditions in Table 2 were selected at the start of the test work as representing the anticipated normal temperature for a full-scale system. "Low Temperature" operations were also selected to observe changes in collection efficiency at temperatures below "normal". The "high temperature" operation represents no cooling of the flue gas.

The normal lime addition rate was calculated on the basis of neutralizing 400 ppm hydrogen chloride and 100 ppm sulphur dioxide plus an excess amount of 20 percent. The "high" lime addition rate was about 20% above the normal rate and the "very high" rate was about 70% above the normal rate. Recycle consisted of ash collected in the fabric filter and was added to the fresh lime at a rate equal to one or two times the fresh lime addition rate.

The direction of the program was influenced by two important developments during the early phase of characterization testing.

- When the particulate concentration at the fabric filter outlet was found to be extremely low (less than 2 mg/Nm^3), it became evident that there would not be enough material collected by the outlet particulate train to analyze for the required metals. This limited the value of particulate sampling at the outlet during characterization and modifications in the sampling procedure were developed for performance testing.
- Only one of the three hydrogen chloride continuous monitors appeared to be operating reliably. Since hydrogen chloride was the most important parameter to study during the characterization test series, it was then decided that more attention should be focused on obtaining as many manual hydrogen chloride samples as possible at the midpoint and outlet. To do this, particulate sampling at these locations was replaced with manual hydrogen chloride sampling. After performance test number 9, particulate testing at the inlet was also replaced by manual hydrogen chloride sampling at that location.

It was also observed during the CT series that the hydrogen chloride concentrations in the flue gas were higher on weekends than during the week. This was attributed to the burning of some wood waste from the neighbouring pulp mill during the week days. Subsequently, the operators of the incinerator were asked to minimize the amount of this material being fed to the no. 3 incinerator and the operators complied.

5.2 Results of Characterization Tests

Sulphur dioxide and hydrogen chloride removal efficiencies were two of the key emission variables examined during the characterization test phase. The following general conclusions were drawn:

- For the dry system, recycling ash from the fabric filter hopper with the fresh lime feed to the scrubber resulted in little or no change in hydrogen chloride and sulphur dioxide removal.
- For the wet-dry system, at low temperature operation, recycling of ash from the fabric filter increased sulphur dioxide removal from 48% to 78%. However, at normal temperature and a high lime addition rate, there was no apparent increase in sulphur dioxide removal, although the subsequent performance tests did show some benefit.
- Lower gas temperature in the scrubber was significantly more favourable for sulphur dioxide removal. Gas temperature did not appear to significantly affect hydrogen chloride removal efficiency, which was typically well over 90%.
- Higher lime feed rates were effective in increasing sulphur dioxide removal efficiency. This is further elaborated in the performance test series. Lime feed rate appeared to have no significant effect on hydrogen chloride collection.
- For both systems, operating conditions were identified to achieve 95-98% hydrogen chloride removal and 80-85% sulphur dioxide removal.
- Similar collection efficiencies were achieved by both systems.
- For both systems, the fabric filter was extremely efficient in removing fly ash and lime from the flue gas, reducing the particulate load from 6000 mg/Nm^3 at the inlet to less than 2 mg/Nm^3 at the outlet.

5.3 Selection of Performance Test Conditions

The rationale for selecting the performance test (PT) conditions was primarily based on an assessment of characterization test results as well as a review of recent test results for similar facilities (6,7,8,9). Six performance test conditions were selected and duplicate runs were conducted at each operating condition to replicate the test results. Based on a review of characterization test results particularly for sulphur dioxide and other Flakt data (7,9), the operating temperature of the scrubber was determined to be the most important independent variable for removal of acid gases, mercury and organic compounds, so a wide range of temperatures was selected. The test conditions selected and rationale are shown in Table 3.

TABLE 3 SELECTION OF PERFORMANCE TEST CONDITIONS

Operating Mode	Target Temp. Before Fabric Filter (°C)	Rationale
Dry System	>300	To collect data with no gas cooling for comparison to the three other temperatures.
	140	Benchmark for comparison with other tests. Considered normal for full-scale.
	125	To observe potential improvements in organic removal at lower than normal temperatures.
	110	To push the limits of low temperature operation, particularly for impact on organics removal.
Wet-Dry System	140	Benchmark for comparison with other tests.
(+ Recycle)	140	To investigate whether lime recycle enhances the removal efficiency of organics and acid gases.

The lime feed rate was maintained at the normal levels established in the characterization tests so that the effect of temperature on removal efficiency could be studied more closely.

For each of the performance test conditions selected, sampling and data collection were conducted as shown in Figure 9.

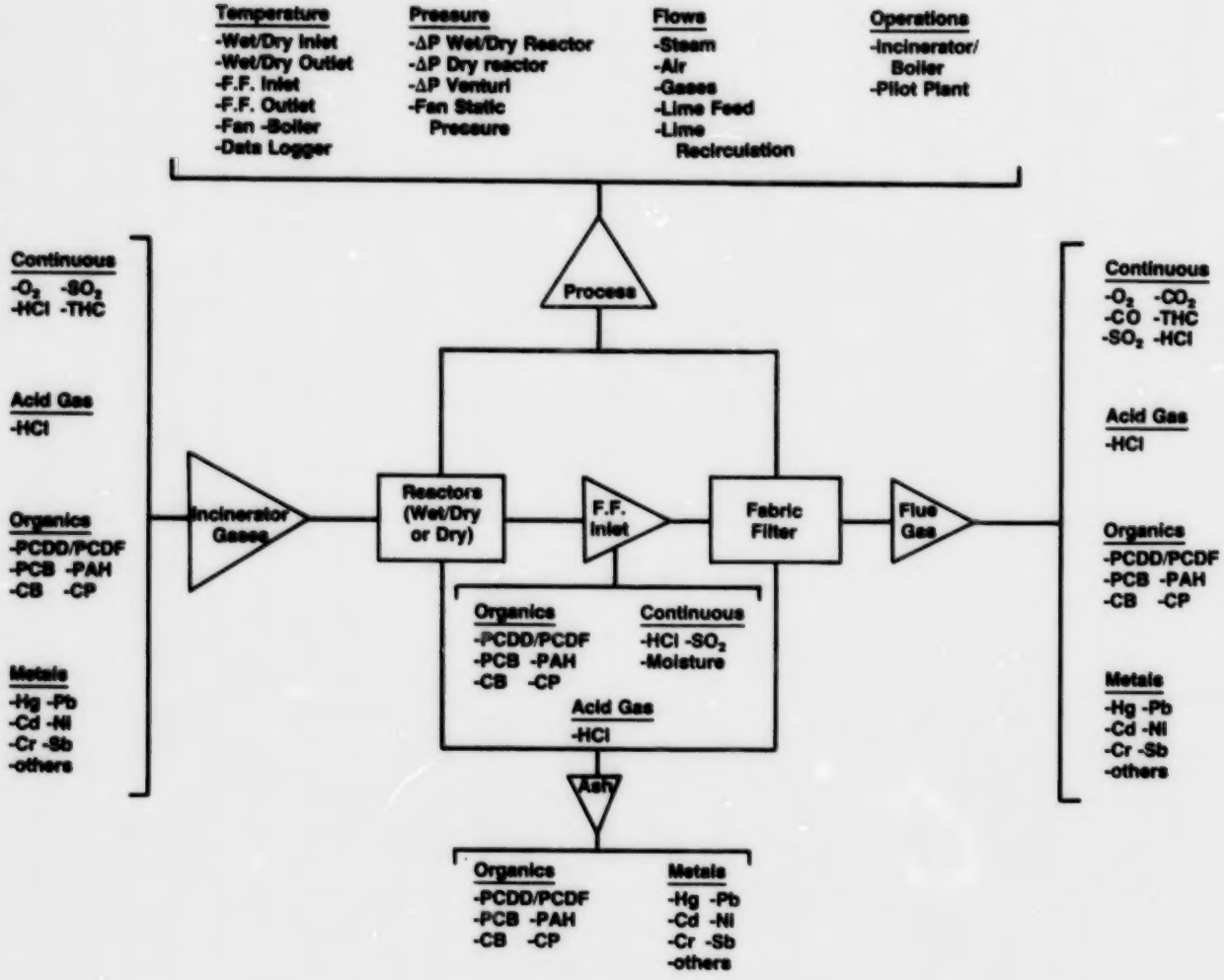


FIGURE 9 SAMPLING/DATA PARAMETERS FOR PERFORMANCE TESTING

6 PERFORMANCE TEST RESULTS

In this section, the performance test results are summarized; key operating data and conventional flue gas data are discussed. Subsequent sections provide discussions of the results for dioxins/furans (section 7), other organics (section 8), metals (section 9) and acid gases (section 10).

Based on the characterization test results, six operating conditions were selected for detailed performance testing and two runs were completed for each condition. The first performance test (PT) was designated as a preliminary test due to some sampling equipment operation problems. The descriptions and test numbers for each of the performance test conditions are shown in Table 4.

TABLE 4 SUMMARY OF PERFORMANCE TEST CONDITIONS

Operating Mode	Temperature Before Fabric Filter		PT No.
	Target °C	Actual °C*	
Dry System	>200	209	5,6
	140	141	1,2,11
	125	125	3,4
	110	113	12,13
Wet-Dry System	140	140	7,8
(+ Recycle)	140	141	9,10

* Thermocouple Data from Pilot Plant Control System.

6.1 Comparison of Test Data Within Each Pair of Runs

For each of the test conditions, there were two individual tests, except for the dry operating mode at 140°C for which there were three tests, PT-1 being a preliminary test. The use of pair averaged data for each pair of tests would simplify the assessment and comparison of the six operating conditions. In order to determine whether the average of any two tests could be used to represent a particular test condition, a detailed review was made of all the data for each test to identify the similarities and differences within each pair of tests.

With regard to plant operating variables, it was relatively easy to maintain the same operating conditions during each pair of runs. Gas temperature after cooling and lime feed rate could be maintained very constant at the pre-selected condition. Incinerator operations were quite stable throughout the test program, representative of normal steam production. Accordingly, the pair average could be used to represent the operating data for each different test condition.

At the inlet as well as at the outlet, the metals data (except mercury) were very similar for all PT pairs, so that the pair average was considered to be representative for data comparisons. For mercury, some inlet results were significantly different within a pair of tests, but this had no significant influence on outlet results. Accordingly, the pair average was used for comparing mercury results among the six test conditions.

Acid gas results, such as hydrogen chloride and sulphur dioxide, were similar for each pair of tests and, accordingly, the test pair average was considered to be a good indication of acid gas removal efficiency for each different test condition.

Organic emission results showed some similarities but at times significant differences occurred between a pair of tests at the same test condition. Upon examination of these data, it was concluded that, in general, pair group averages provided a relative indication of emission levels. However, organics data for some test runs were significantly different between pairs of tests and this must be considered when comparing pair averages.

Operating conditions and emissions were compared, therefore, on the basis of test condition averages. The pair average results at each sampling location are summarized in Figures 10 to 15 for the six performance test operating conditions.

6.2 Test Condition Averages

6.2.1 Incinerator and Pilot Plant Operating Data. The key operating data are summarized in the Table 5.

- Incinerator - The incinerator was operated normally, in a stable manner for all the performance tests except for PT-13, when the incinerator was rather unstable all day. The testing program was interrupted only once (15 minutes) during PT-8 when a blockage occurred in the feed chute to the incinerator. During performance testing, the average steam flow was between 31 and 34 thousand kilograms per hour. The average temperature of the flue gases after the waste heat boiler was between 278 and 303°C. The operators of the incinerator were very cooperative in maintaining no. 3 stable and avoided burning wood waste from the adjacent pulp and paper mill.

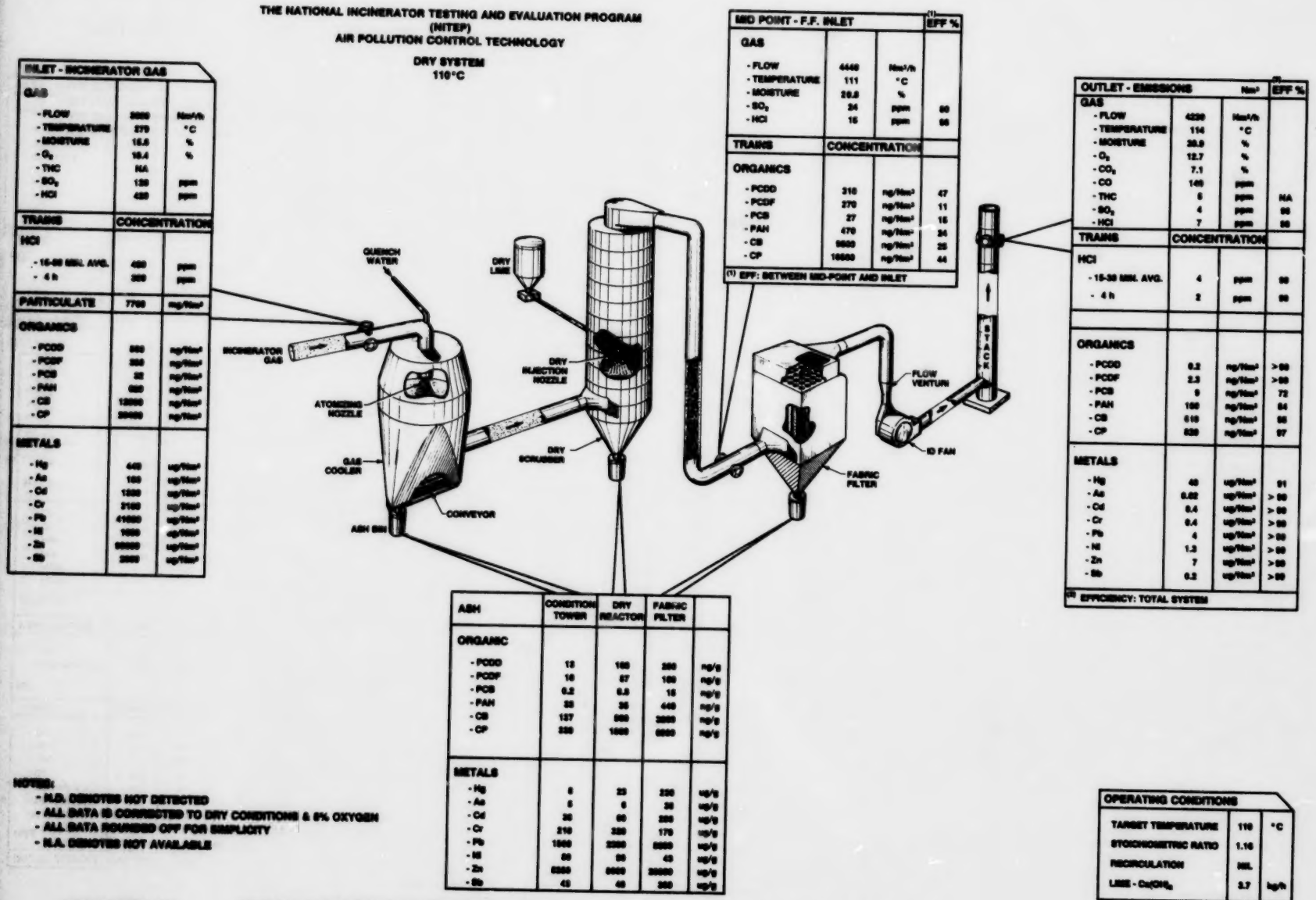
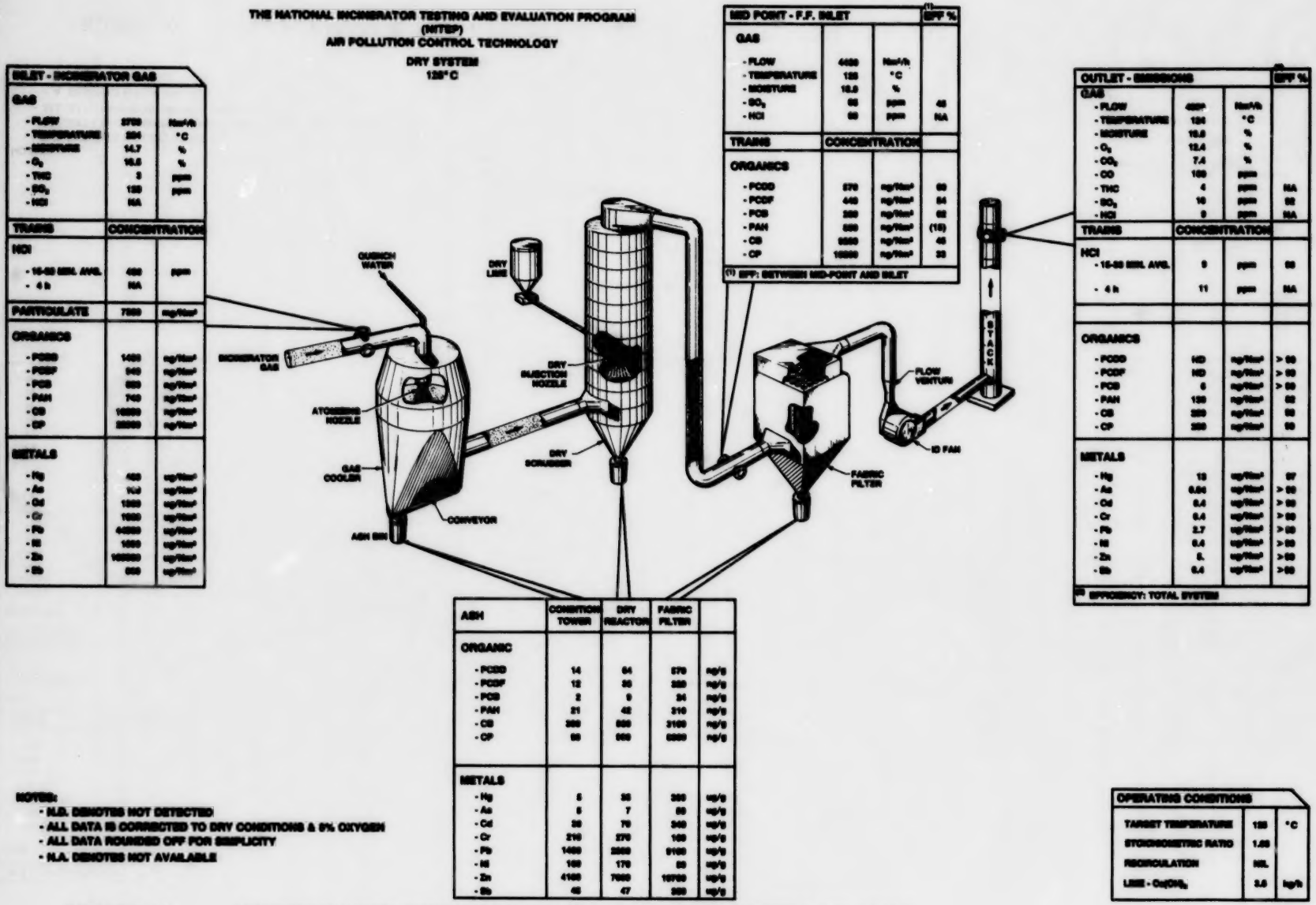


FIGURE 10 PERFORMANCE TEST RESULTS (PT-12, 13) - DRY SYSTEM AT 110°C



INLET - INCINERATOR GAS		
GAS		
- FLOW	5700	Nm³/h
- TEMPERATURE	250	°C
- MOISTURE	12.7	%
- O_2	10 - 12	%
- THC	100	ppm
- SO_2	NA	ppm
- HCl		ppm
TRACE	CONCENTRATION	
HCl		
- 15-60 MIN. AVG.	450	ppm
- 4 h	NA	ppm
PARTICULATE	7000	mg/Nm³
ORGANICS		
- PCDD	140	ng/Nm³
- PCDF	70	ng/Nm³
- PCB	20	ng/Nm³
- PAH	70	ng/Nm³
- CB	1000	ng/Nm³
- CP	5000	ng/Nm³
METALS		
- Hg	0.8	mg/Nm³
- As	0.2	mg/Nm³
- Cd	0.5	mg/Nm³
- Cr	0.5	mg/Nm³
- Pb	0.5	mg/Nm³
- Ni	0.5	mg/Nm³
- Zn	1.0	mg/Nm³
- Sb	0.5	mg/Nm³

MID POINT - F.F. INLET			EFF %
GAS			
- FLOW	4400	Nm³/h	
- TEMPERATURE	150	°C	
- MOISTURE	12.5	%	
- SO_2	60	ppm	40
- HCl	60	ppm	NA
TRACE	CONCENTRATION		
ORGANICS			
- PCDD	370	ng/Nm³	80
- PCDF	440	ng/Nm³	84
- PCB	380	ng/Nm³	80
- PAH	880	ng/Nm³	(10)
- CB	6000	ng/Nm³	40
- CP	10000	ng/Nm³	33

(1) EFF: BETWEEN MID-POINT AND INLET

OUTLET - EMISSIONS			EFF %
GAS			
- FLOW	4600	Nm³/h	
- TEMPERATURE	124	°C	
- MOISTURE	12.8	%	
- O_2	12.4	%	
- CO_2	7.4	%	
- CO	100	ppm	
- THC	4	ppm	NA
- SO_2	16	ppm	60
- HCl	9	ppm	NA
TRACE	CONCENTRATION		
HCl			
- 15-60 MIN. AVG.	9	ppm	80
- 4 h	11	ppm	NA
ORGANICS			
- PCDD	ND	ng/Nm³	> 80
- PCDF	ND	ng/Nm³	> 80
- PCB	4	ng/Nm³	> 80
- PAH	120	ng/Nm³	80
- CB	300	ng/Nm³	80
- CP	300	ng/Nm³	80
METALS			
- Hg	10	ug/Nm³	80
- As	0.04	ug/Nm³	> 80
- Cd	0.4	ug/Nm³	> 80
- Cr	0.4	ug/Nm³	> 80
- Pb	2.7	ug/Nm³	> 80
- Ni	0.4	ug/Nm³	> 80
- Zn	0.4	ug/Nm³	> 80
- Sb	0.4	ug/Nm³	> 80

(2) EFFICIENCY: TOTAL SYSTEM

ASH	CONDITION TOWER	DRY REACTOR	FABRIC FILTER	
ORGANIC				
- PCDD	14	84	570	ng/g
- PCDF	12	35	300	ng/g
- PCB	2	9	34	ng/g
- PAH	21	42	210	ng/g
- CB	300	600	2100	ng/g
- CP	60	600	6000	ng/g
METALS				
- Hg	0	35	300	ug/g
- As	0	7	60	ug/g
- Cd	35	70	340	ug/g
- Cr	210	270	100	ug/g
- Pb	1400	2000	9100	ug/g
- Ni	100	170	60	ug/g
- Zn	4100	7000	10700	ug/g
- Sb	40	47	300	ug/g

NOTES:
- N.D. DENOTES NOT DETECTED
- ALL DATA IS CORRECTED TO DRY CONDITIONS & 8% OXYGEN
- ALL DATA ROUNDED OFF FOR SIMPLICITY
- N.A. DENOTES NOT AVAILABLE

OPERATING CONDITIONS		
TARGET TEMPERATURE	150	°C
STOICHIOMETRIC RATIO	1.60	
RECIRCULATION	NIL	
LIME - $Ca(OH)_2$	2.5	kg/h

FIGURE 11 PERFORMANCE TEST RESULTS (PT-3, 4) - DRY SYSTEM AT 125°C

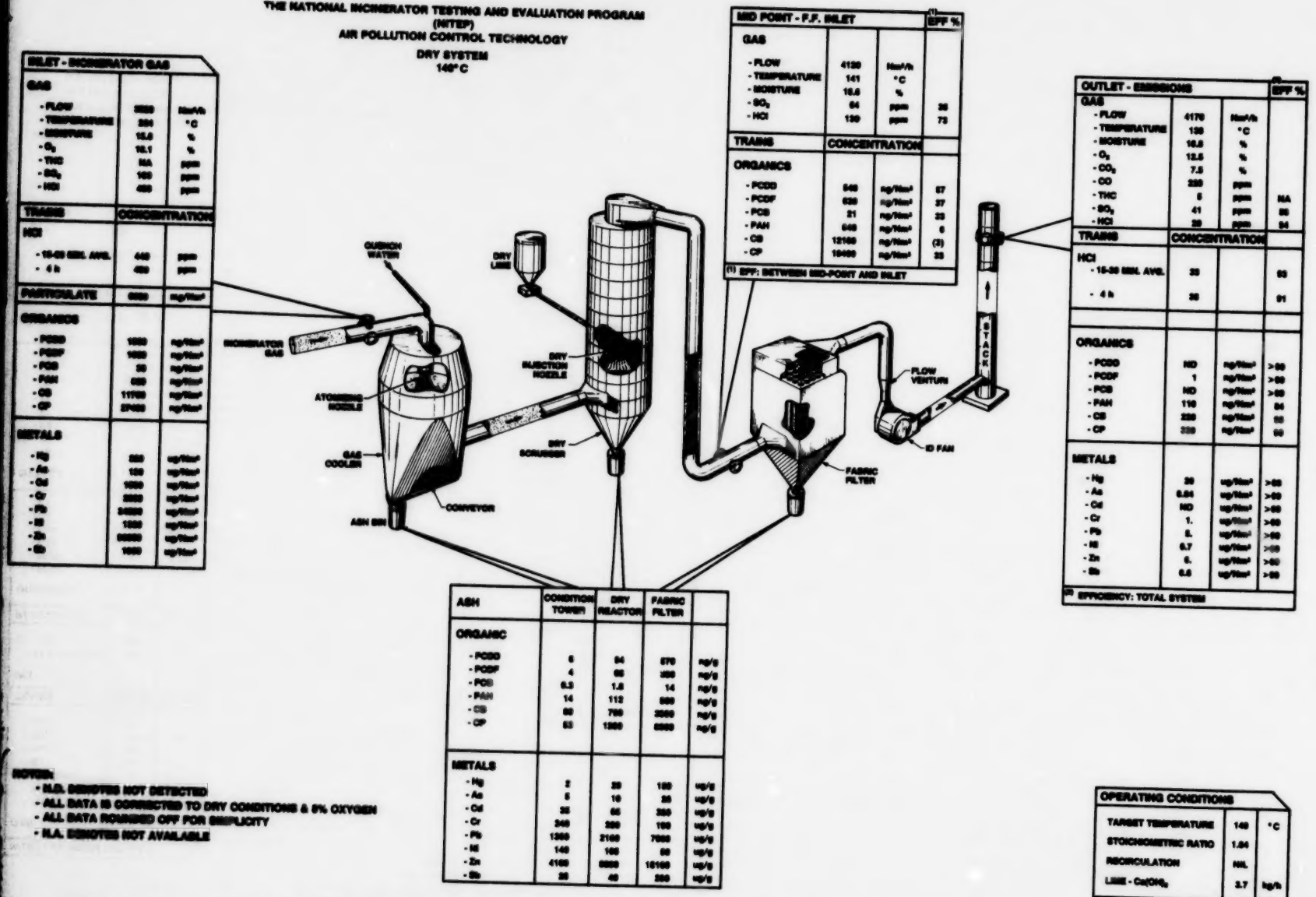


FIGURE 12 PERFORMANCE TEST RESULTS (PT-2, 11) - DRY SYSTEM AT 140°C

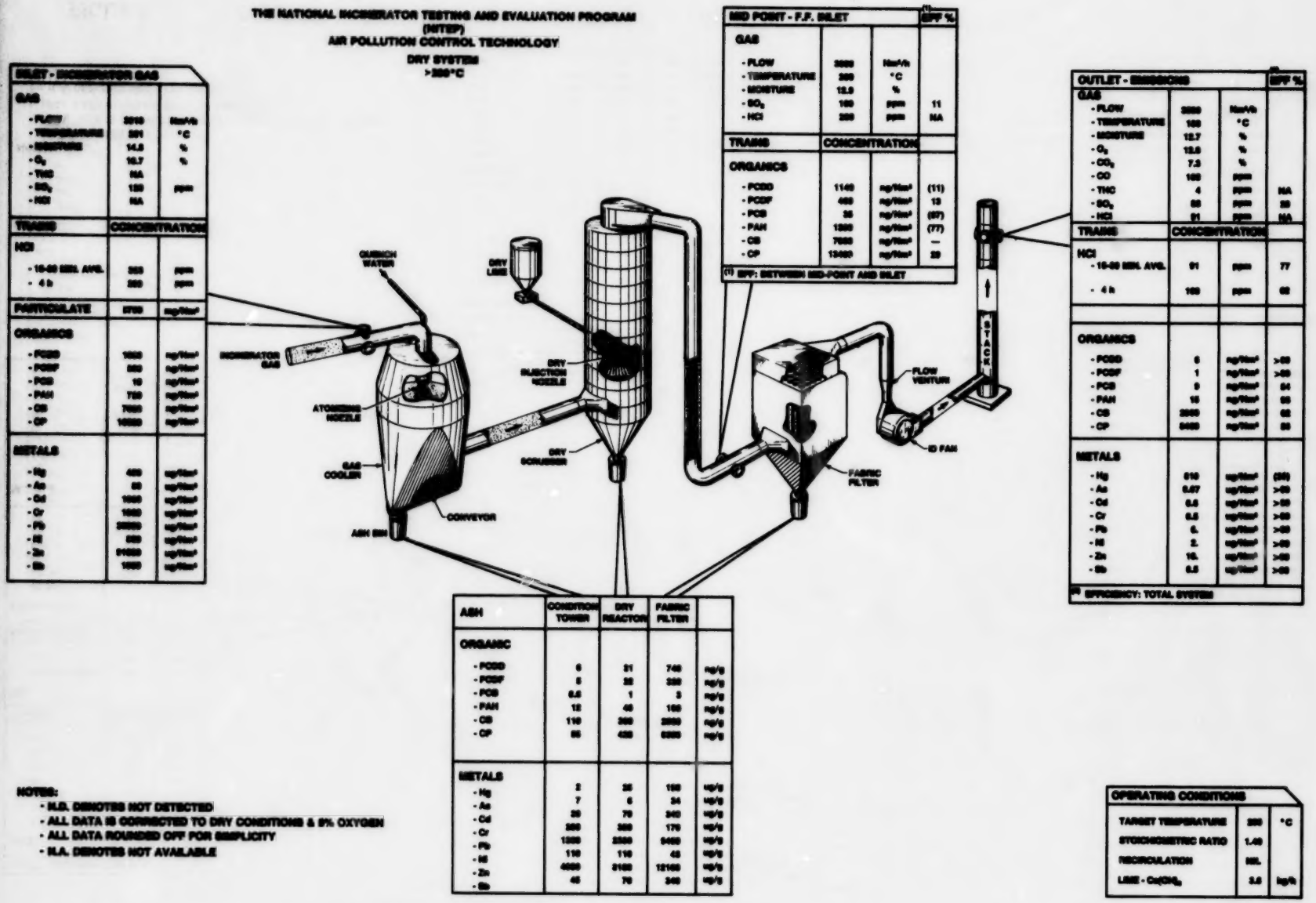


FIGURE 13 PERFORMANCE TEST RESULTS (PT-5, 6) - DRY SYSTEM AT > 200°C

THE NATIONAL INCINERATOR TESTING AND EVALUATION PROGRAM
(NITEP)
AIR POLLUTION CONTROL TECHNOLOGY
WET-DRY SYSTEM
140°C (NO RECYCLE)

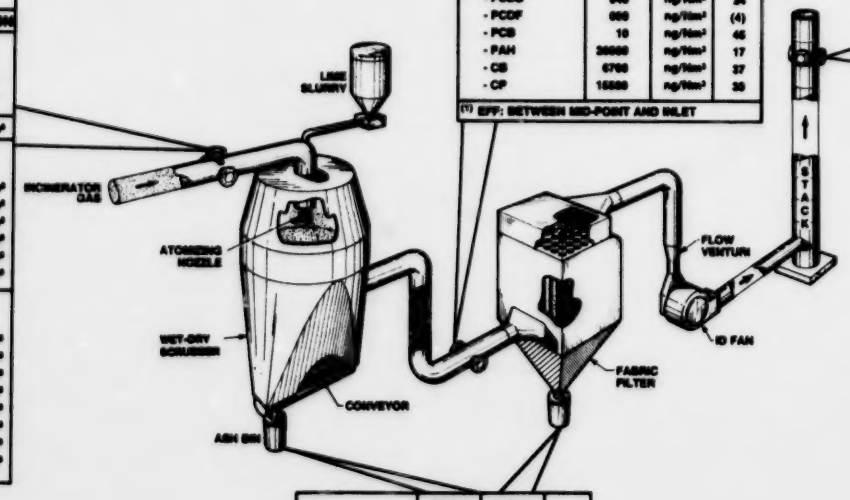
INLET - INCINERATOR GAS		
GAS		
- FLOW	3680	Nm³/h
- TEMPERATURE	260	°C
- MOISTURE	16.2	%
- O_2	8.8	%
- THC	NA	
- SO_2	110	ppm
- HCl	330	ppm
TRAINS	**CONCENTRATION**	
HCl		
- 30 MIN. AVG.	410	ppm
- 4 h	330	ppm
PARTICULATE	5500	mg/Nm³
ORGANICS		
- PCDD	1100	ng/Nm³
- PCDF	800	ng/Nm³
- PCB	10	ng/Nm³
- PAH	24000	ng/Nm³
- CB	16000	ng/Nm³
- CP	22000	ng/Nm³
METALS		
- Hg	160	ug/Nm³
- As	110	ug/Nm³
- Cd	1300	ug/Nm³
- Cr	1400	ug/Nm³
- Pb	28000	ug/Nm³
- Ni	700	ug/Nm³
- Zn	77000	ug/Nm³
- Sb	1600	ug/Nm³

MID POINT - F.F. INLET			(1) EFF %
GAS			
- FLOW	4100	Nm³/h	
- TEMPERATURE	150	°C	
- MOISTURE	16.2	%	
- SO_2	67	ppm	37
- HCl	160	ppm	55
TRAINS	**CONCENTRATION**		
ORGANICS			
- PCDD	640	ng/Nm³	34
- PCDF	650	ng/Nm³	(4)
- PCB	10	ng/Nm³	46
- PAH	20000	ng/Nm³	17
- CB	6700	ng/Nm³	37
- CP	15500	ng/Nm³	30

(1) EFF: BETWEEN MID-POINT AND INLET

OUTLET - EMISSIONS			(2) EFF %
GAS			
- FLOW	4200	Nm³/h	
- TEMPERATURE	135	°C	
- MOISTURE	16.1	%	
- O_2	11.8	%	
- CO_2	8.3	%	
- CO	130	ppm	
- THC	4	ppm	NA
- SO_2	35	ppm	67
- HCl	30	ppm	91
TRAINS	**CONCENTRATION**		
HCl			
- 30 MIN. AVG.	35	ppm	91
- 4 h	47	ppm	86
ORGANICS			
- PCDD	ND	ng/Nm³	>98
- PCDF	ND	ng/Nm³	>98
- PCB	ND	ng/Nm³	>98
- PAH	110	ng/Nm³	>98
- CB	88	ng/Nm³	>98
- CP	340	ng/Nm³	98
METALS			
- Hg	16.	ug/Nm³	90
- As	0.84	ug/Nm³	>99%
- Cd	ND	ug/Nm³	>99%
- Cr	0.2	ug/Nm³	>99%
- Pb	1.	ug/Nm³	>99%
- Ni	1.	ug/Nm³	>99%
- Zn	5.	ug/Nm³	>99%
- Sb	0.3	ug/Nm³	>99%

(2) EFFICIENCY: TOTAL SYSTEM



ASH	SPRAY REACTOR	FABRIC FILTER	
ORGANIC			
- PCDD	6	160	ng/g
- PCDF	8	150	ng/g
- PCB	0.3	5	ng/g
- PAH	210	3500	ng/g
- CB	160	1600	ng/g
- CP	44	2700	ng/g
METALS			
- Hg	2	70	ug/g
- As	5	15	ug/g
- Cd	30	100	ug/g
- Cr	170	100	ug/g
- Pb	1300	8100	ug/g
- Ni	70	100	ug/g
- Zn	3000	10000	ug/g
- Sb	35	100	ug/g

NOTES:
- N.D. DENOTES NOT DETECTED
- ALL DATA IS CORRECTED TO DRY CONDITIONS & 6% OXYGEN
- ALL DATA ROUNDED OFF FOR SIMPLICITY
- N.A. DENOTES NOT AVAILABLE

OPERATING CONDITIONS		
TARGET TEMPERATURE	140	°C
STOICHIOMETRIC RATIO	1.10	
RECIRCULATION	NIL	
LIME - $Ca(OH)_2$	3.8	kg/h

FIGURE 14 PERFORMANCE TEST RESULTS (PT-7, 8) - WET-DRY SYSTEM AT 140°C (NO RECYCLE)

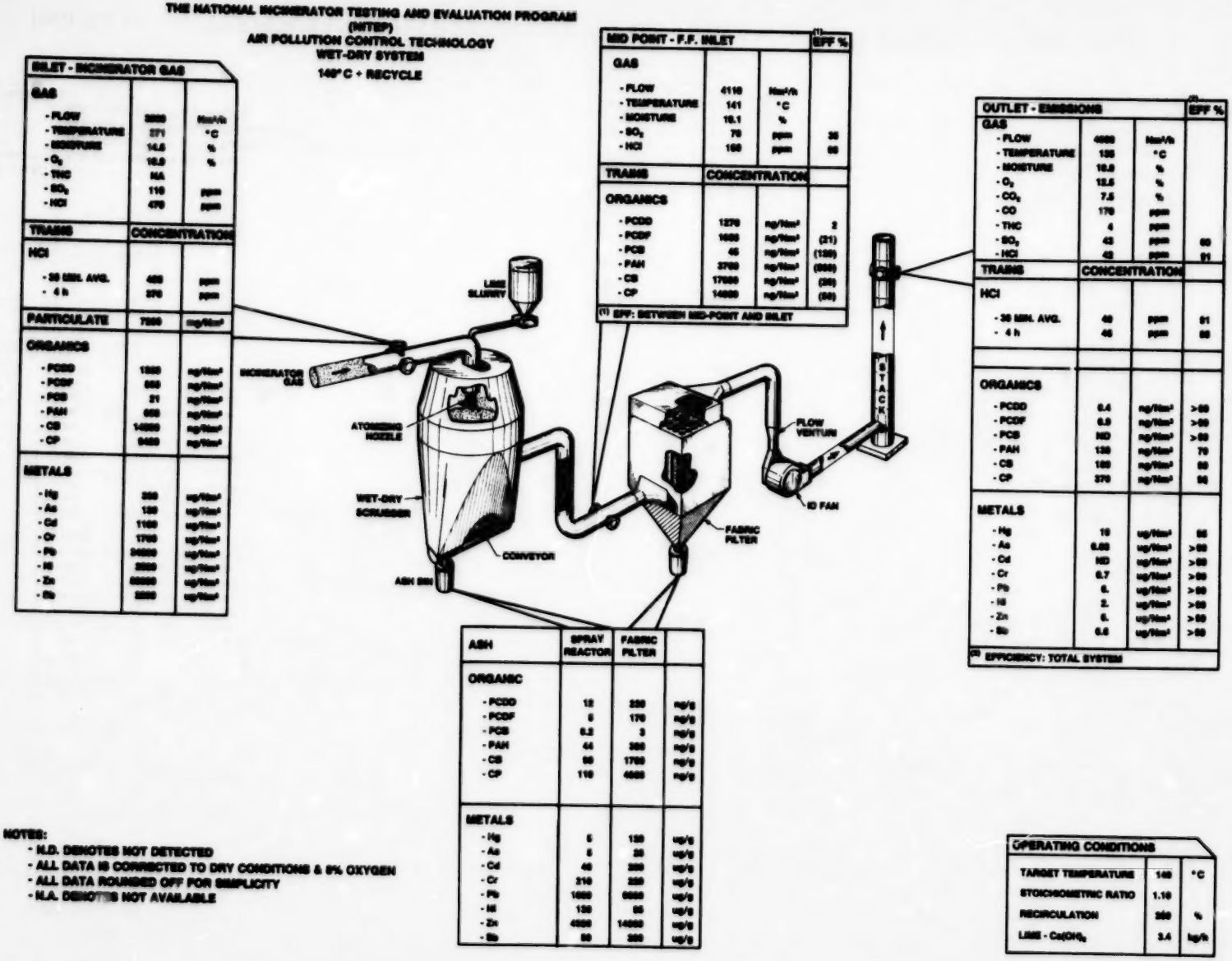


FIGURE 15 PERFORMANCE TEST RESULTS (PT-9, 10) - WET-DRY SYSTEM AT 140°C (WITH RECYCLE)

TABLE 5 SUMMARY OF KEY OPERATING PARAMETERS

	Dry System				Wet-Dry System	
	110°C	125°C	140°C	>200°C	140°C	140°C "Recycle"
INCINERATOR						
- Steam Flow (kg/h x 10^3)	32.8	33.4	33.2	33.0	32.1	31.3
- Gas Temp.-Boiler Outlet (°C)	303	287	291	287	278	293
FABRIC FILTER						
- Pressure Drop (cm water gauge)	15.7	14.4	14.9	14.7	15.2	15.9
LIME						
- Flow (kg/h)	3.7	3.6	3.7	3.6	3.5	3.5
TEMPERATURE (°C)*						
- Inlet to Pilot Plant	267	258	261	253	254	263
- Inlet to Fabric Filter	113	125	142	209	140	141

* Thermocouple data from pilot plant control system.

- Pilot Plant - The key operating parameters for the pilot plant were fabric filter pressure drop, the hydrated lime flow rate and the flue gas temperature after cooling. The fabric filter pressure drop was manually adjusted by controlling the air pulsing rate to maintain an average pressure drop of between 14 and 16 centimetres water gauge. The lime slurry flow rate could be maintained within 15 percent of the selected rate during each test. The lime slurry feed pump flow rate had to be slightly increased as the test progressed, because the lime slurry levels decreased in the slurry storage tank, which changed the slurry transfer pump pressure. The dry feeding system did not usually require adjusting at all during the test. The dry lime feed rate varied by less than 10% during any one test. The temperature of the flue gases after cooling (inlet to fabric filter) was controlled to ± 3 °C during each test.

6.2.2 Conventional Flue Gas Data. Standard flue gas parameters such as flow rate and composition are presented below.

Flue Gas Flow Rates - Flue gas flow rates at the three sampling locations are shown in Table 6.

TABLE 6 FLUE GAS FLOW RATES

	Dry System				Wet-Dry System	
	110°C	125°C	140°C	>200°C	140°C	140°C +Recycle
Actual m^3/h						
- Midpoint	7130	7150	7030	6650	7080	7010
N m^3/h (Dry)*						
- Inlet	3600	3730	3520	3010	3650	3560
- Midpoint	4440	4430	4120	3650	4180	4110
- Outlet	4230	4350	4170	3600	4220	4090

*Reference conditions are 25°C and 101.325 kPa.

The flue gas flow rate for each test run and throughout the program was set at approximately 7000 actual cubic metres per hour at the fabric filter and was maintained constant by monitoring pressure drop across a venturi upstream of the fan. The differences between pairs of tests were small, so averages were used to represent each test condition.

Air inleakage across the scrubbers was approximately 20%, as shown by comparison of inlet and mid-point data in Table 6. Some air was intentionally added with the lime injection system. Most of the inleakage has been attributed to tramp air being introduced by the many sampling trains operated during testing. However, inleakage across the fabric filter (i.e., between midpoint and outlet) was insignificant. To compare data from all three sampling locations on a common basis, inleakage was accounted for by correcting all concentrations to 8% oxygen, which is an equivalent similar to 12% carbon dioxide. Since oxygen was measured at both the inlet and the outlet, but carbon dioxide was measured only at the outlet, oxygen was selected as the common basis for data comparisons. Since inleakage across the fabric filter was insignificant, oxygen at the mid-point was assumed to be equal to oxygen at the outlet.

Gas Composition - The conventional combustion gas parameters measured at the outlet sampling location are summarized in Table 7.

TABLE 7 COMBUSTION GAS COMPOSITION AT OUTLET

	Dry System				Wet-Dry System	
	110°C	125°C	140°C	>200°C	140°C	140°C +Recycle
CO_2 (%)	7.1	7.4	7.5	7.3	8.3	7.5
O_2 (%)	12.7	12.4	12.5	12.9	11.8	12.5
CO (ppm)	140	180	220	160	130	170
THC (ppm)	5	4	5	4	4	4

During most of the test program, few changes to the combustion gas composition were recorded. Total hydrocarbons (THC) were at the lower detection limit of the analyzers and showed no significant variation. Oxygen and carbon dioxide varied little other than during the wet-dry mode of operation. Nevertheless, these fluctuations were considered normal. In the case of carbon monoxide, more fluctuation was observed, which is normal for older mass burning incinerators. Overall, the gas compositions appear to be typical of a normally run mass burning incinerator.

Particulate Results - The particulate load from the incinerator to the pilot plant was measured in the range of 5500 to 7700 mg/Nm^3 corrected to 8% oxygen, which is typical of uncontrolled emissions from a mass burning incinerator (9, 10). The results per test condition are shown in Table 8.

TABLE 8 PARTICULATE CONCENTRATION AT INLET

	Dry System				Wet-Dry System	
	110°C	125°C	140°C	>200°C	140°C	140°C +Recycle
Inlet Particulates (mg/Nm^3 @ 8% O_2)	7710	7260	6250	5740	5560	7190

Since the concentration of particulates at the fabric filter outlet was determined during characterization testing to be extremely low (less than 2 mg/Nm^3), no measurements were made during performance testing. Instead, the particulate sampling train became dedicated for collecting particulates for metal analyses.

Typical emissions from fabric filters are reported by various other studies to be about 4-40 mg/Nm^3. For example, the Flakt dry scrubber/fabric filter installations at Sysav, Sweden (7), at Kempten, Germany (9) and at Geiselballach, Germany (12) all achieved particulate emissions of 4-5 mg/Nm^3. A dry scrubber/fabric filter system at a hazardous waste incinerator in Finland achieved particulates between 10 and 20 mg/Nm^3 at the stack (11). A dry scrubber/fabric filter system at Tsushima, Japan, was reported to emit as low as 25 mg/Nm^3 but generally was much higher (8). In comparison, the three-field electrostatic precipitator (guaranteed for 65 mg/Nm^3) at Westchester, N.Y., achieved about 35 mg/Nm^3 in a recent test (13). The four-field precipitator in Baltimore is reported to have achieved 20 mg/Nm^3 (4).

Particulate emissions from Flakt's pilot plant were of the same order of magnitude as Flakt's full scale installations. New Teflon filterbags and a "bubble tight" by-pass damper contributed to the very low emissions achieved. As anticipated, emissions were less than typically achieved by highly efficient electrostatic precipitators.

Ash Collection Rates - All the ashes removed by the vessels were collected and weighed during each test. However, due to residual ash adhering to some vessel walls and in particular to the fabric filter bags, these data were not accurate enough to determine a mass balance. The approximate percentage distribution of total ash collected by the pilot plant was estimated by Flakt and is shown in Table 9. These proportions provide some insight when reviewing concentrations of various contaminants in the ash.

TABLE 9 PROPORTION OF ASH COLLECTED IN EACH VESSEL
(Note: Excludes incinerator bottom ash and boiler ash)

Source of Ash	Dry System	Wet-Dry System
Wet-Dry Scrubber (or Conditioning Tower)	30%	33%
Dry Scrubber	40%	-
Fabric Filter	30%	67%
	100%	100%

7 DIOXIN/FURAN RESULTS

To address public concern about emissions of polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) from EFW facilities, these compounds were measured in the flue gases at the inlet, midpoint and outlet of the pilot scale system, as well as in the ashes collected by the hoppers of the scrubbers and fabric filter. The significant amount of data obtained is summarized in tabular and graphical forms in this section. Removal efficiencies are presented to evaluate system performance. Homologue distributions are shown, since the toxicity of each homologue group is different. As each data set is presented, the key observations and data interpretation are highlighted.

7.1 Dioxins in Flue Gas

The concentration of dioxins (PCDD) in the flue gas at the three sampling locations and the removal efficiencies under various operating conditions are shown in Table 10. PCDD concentrations in the flue gas at the three sampling locations are also presented in the bar charts in Figure 16 to illustrate the impact on removal of PCDD by the scrubbers and the fabric filter.

TABLE 10 PCDD CONCENTRATIONS (ng/Nm^3 @ 8% O_2) IN FLUE GAS AND EFFICIENCY OF REMOVAL

	Dry System				Wet-Dry System	
Operating Condition	110°C	125°C	140°C*	>200°C	140°C	140°C +Recycle
Inlet (ng/Nm^3)	580	1400	1300	1030	1100	1300
Mid Point (ng/Nm^3)	310	570	540	1140	840	1270
Outlet (ng/Nm^3)	0.2	ND	ND	6.1	ND	0.4
Efficiency (%)						
- Inlet/Midpoint	47	60	57	(11)	24	2
- Overall	>99.9	> 99.9	> 99.9	99.4	> 99.9	> 99.9

( ) denotes negatives.
* Based on 1 test.
ND = Not Detected

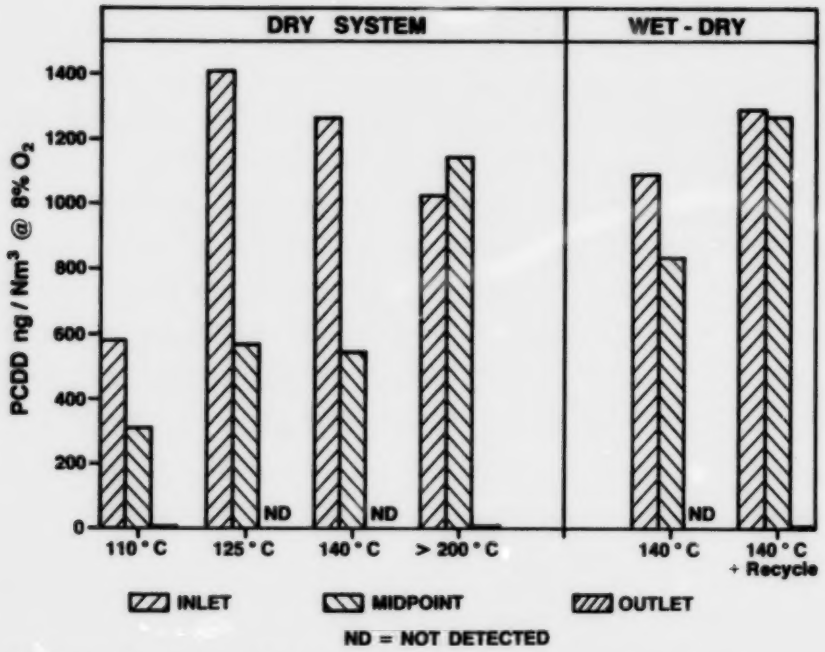


FIGURE 16 PCDD CONCENTRATIONS IN FLUE GAS

The dioxin data demonstrates the following key points:

- The overall removal of PCDD was very significant; greater than 99.9% efficiency was achieved for all operating conditions tested except for the high temperature (>200°C) condition, where the efficiency was 99.4%, which is still very significant. Unpublished results from a Flakt dry scrubber/fabric filter pilot at Studsvik, Sweden, have recently shown 98-99% dioxin removal efficiency at 124 to 160°C (14). High removal of PCDD (over 99% at 120°C) has been reported for a pilot scale incinerator equipped with dry scrubber/fabric filter (6), but the efficiency was lower, 84%, at 160°C.
- Inlet PCDD concentrations averaged 1100 ng/Nm^3 at 8% oxygen, which appears to be typical for older conventional mass burning incinerators (3).
- Outlet PCDD concentrations were extremely low (all below 6 ng/Nm^3) and were "not detectable" for most of the test runs.
- At the mid-point sampling location, PCDD concentrations were 25% to 60% less than at the inlet for four of the operating conditions. However, two operating conditions showed essentially no change: the >200°C case and the wet-dry condition with recycle.

Dioxins are a family of 75 compounds which are grouped into homologues, as explained in the Appendix. Since each homologue has a different toxicity equivalent, the homologue distributions of dioxins at each of the three sampling locations are shown in Figure 17 for each of the six operating conditions tested.

The following key points should be noted about the PCDD homologues:

- The PCDD homologue distribution was similar for all operating conditions.
- At the inlet and mid-point, the dioxin homologue distribution is bell shaped and skewed to the higher molecular weight compounds, particularly the hexa, hepta and octa compounds.
- In all tests, the most toxic homologue (i.e., the tetra) showed the least concentration.
- At the outlet, three operating conditions showed no detectable levels of any PCDD homologue. The other three operating conditions showed detectable quantities of hexa, hepta and octa compounds, but no penta. Only one operating condition (wet-dry mode with recycle) showed a detectable level of tetra compounds, plus some amounts of hexa and hepta.

7.2 Furans in Flue Gas

Furan (PCDF) concentrations in the flue gas for the three sampling locations are summarized in Table 11 and Figure 18.

The PCDF results show the following key points:

- The overall removal of PCDF was greater than 99.3% for all operating conditions, which is considered to be very significant. These PCDF results are in agreement with data on PCDF removal in reference 6, except that higher temperature did not decrease efficiency as much as reported in reference 6.
- Inlet PCDF concentrations averaged about 700 ng/Nm^3 at 8% oxygen, which is about one-third less than the inlet PCDD concentration of 1100 ng/Nm^3 at 8% oxygen.
- At the outlet, PCDF concentrations were reduced to less than 3 ng/Nm^3 for all operating conditions.
- At the midpoint location, PCDF concentrations were 10 to 50% less than at the inlet for the dry operating mode. However, for the wet-dry operating mode, a slight increase was found.

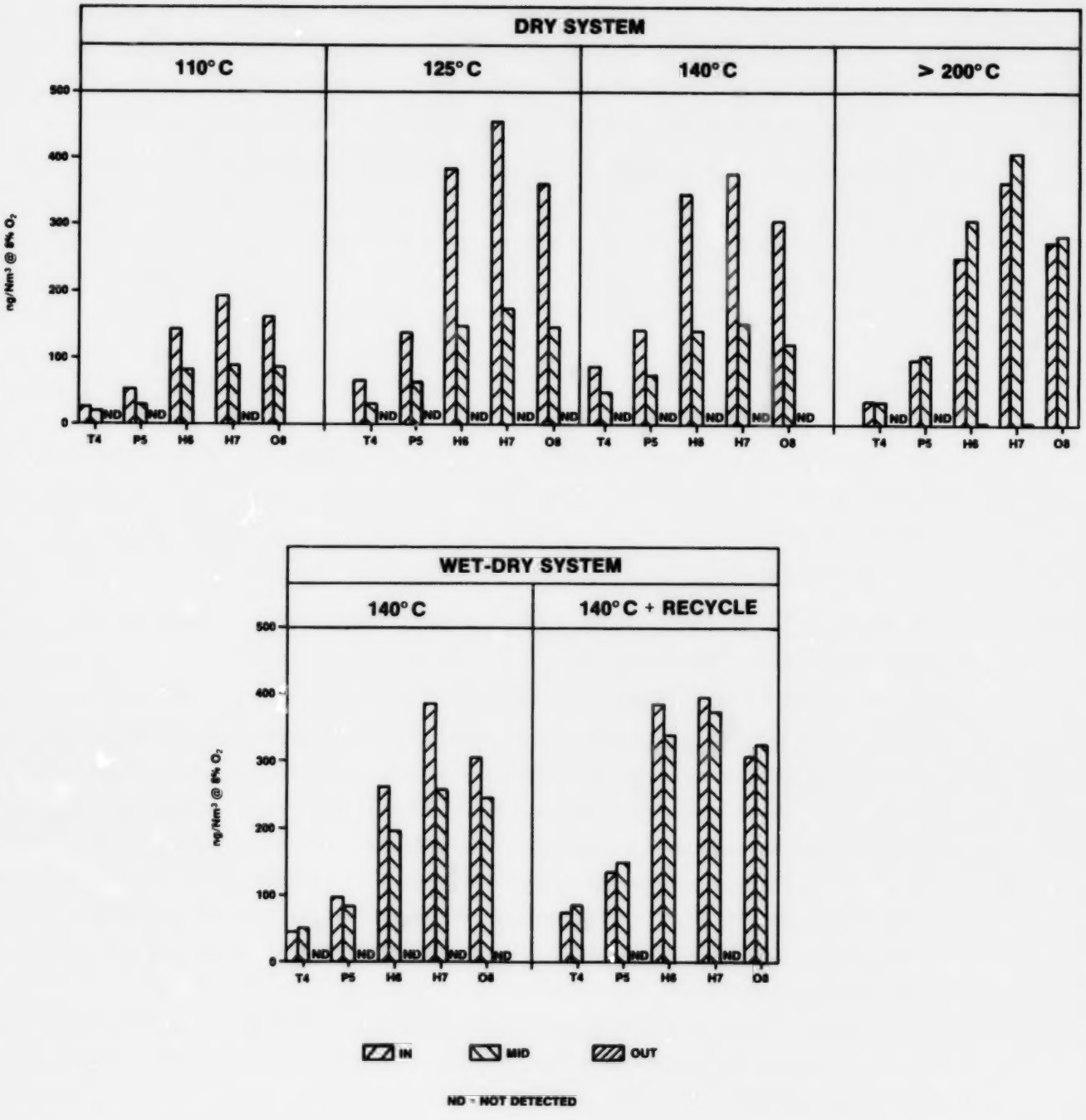


FIGURE 17 PCDD HOMOLOGUE DISTRIBUTION IN FLUE GAS

TABLE 11 PCDF CONCENTRATIONS (ng/Nm^3 at 8% O_2) IN FLUE GAS AND EFFICIENCY OF REMOVAL

Operating Condition	Dry System				Wet-Dry System	
	110°C	125°C	140°C*	>200°C	140°C	140°C +Recycle
Inlet (ng/Nm^3)	300	940	1000	560	660	850
Mid Point (ng/Nm^3)	270	440	630	490	690	1030
Outlet (ng/Nm^3)	2.3	ND	1.0	1.2	ND	0.9
Efficiency (%)						
- Inlet/Midpoint	11	54	37	13	-4	-21
- Overall	99.3	>99.9	99.9	99.8	>99.9	99.9

* Based on one test.
ND = Not Detected

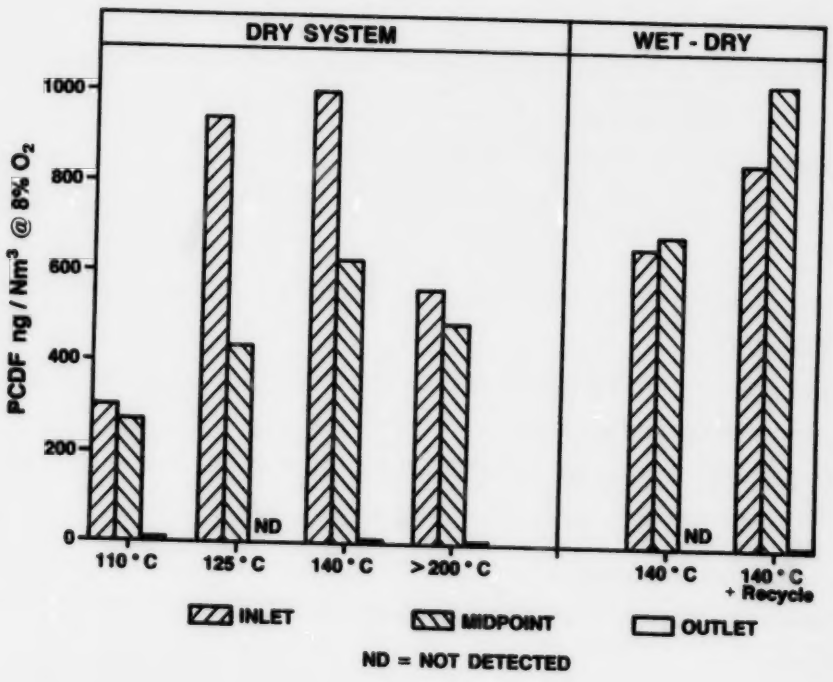


FIGURE 18 PCDF CONCENTRATIONS IN FLUE GAS

As in the case of dioxins, furans are a family of 135 compounds, grouped into homologues, each with a different toxicity. The homologue distributions of furans at each of the three sampling locations are shown in Figure 19 for each of the operating conditions tested.

Key observations about PCDF homologues are as follows:

- The PCDF homologue distributions at both the inlet and the mid-point were very similar. The highest concentrations occurred for the lower molecular weight compounds, gradually decreasing with increases in molecular weight.
- At the outlet, two test conditions showed only the hepta compounds, two showed "not detectable" levels of all homologues and two conditions showed detectable levels of tetra, penta, hexa and hepta compounds.

7.3 Dioxins in Hopper Ashes

As the incinerator flue gas flows through the gas scrubbing system, some fly ash falls out in the scrubbers and the balance of the fly ash (plus lime) is removed in the fabric filter. The approximate proportion of the ash collected by each vessel was discussed in Section 6.

The concentration (ng/g) of PCDD in the hopper ashes of the three vessels are summarized in Table 12. The data are also presented in bar chart form in Figure 20 to better visualize the relative concentration in each of the ashes.

The key observations for PCDD concentration in the hopper ashes are as follows:

- The highest concentration of PCDD was found in the fabric filter for all test conditions (200 to 700 ng/g).
- In the dry mode, a progressive increase of PCDD concentration was observed in the ashes as the gas flowed through the system.
- For the lowest temperature condition (110°C), there appears to be a shift in distribution of PCDD concentrations to the dry scrubber (160 ng/g).

When estimates of the proportion of ash collected in each vessel are combined with the PCDD concentrations in the ash, a weighted average for PCDD concentrations in the ashes shows the following:

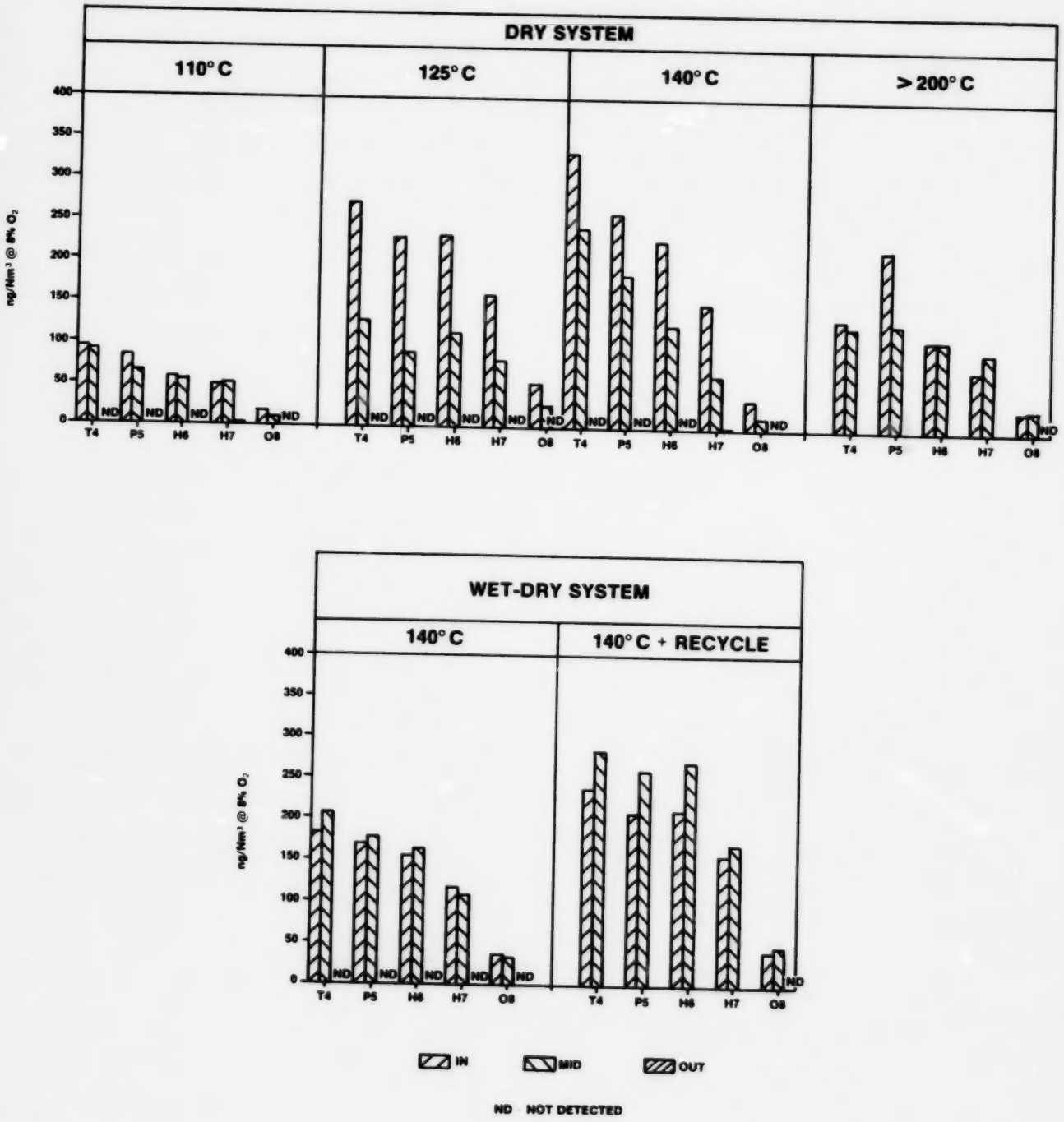


FIGURE 19 PCDF HOMOLOGUE DISTRIBUTION IN FLUE GAS

TABLE 12 PCDD (ng/g) CONCENTRATIONS IN ASH

Operating Condition	Dry System				Wet-Dry System	
	110°C	125°C	140°C	>200°C	140°C	140°C +Recycle
Wet-Dry Scrubber Ash	13	14	6	6	6	12
Dry Scrubber Ash	160	64	94	31	N/A	N/A
Fabric Filter Ash	280	570	570	740	160	230

N/A = Not Applicable

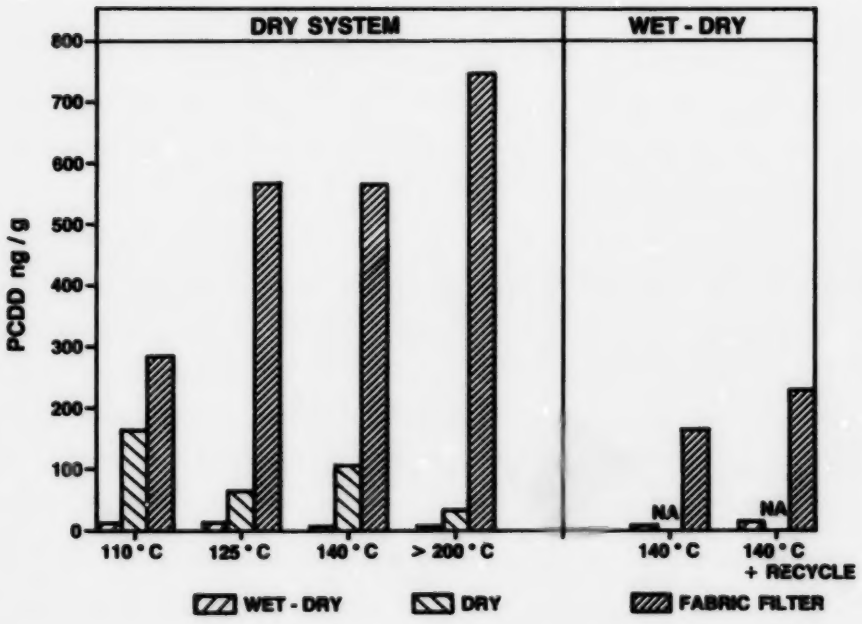


FIGURE 20 PCDD CONCENTRATIONS IN HOPPER ASHES

- In the dry system, about 80% of total PCDD found in the ashes was in the fabric filter ash and 17% was in the dry scrubber ash. In comparison, 30% of the total ash collected by the pilot plant was the fabric filter ash and 40% was the dry scrubber ash, the balance being the gas cooler ash. Accordingly, most of the PCDD in the ashes ends up in the fabric filter ash, which is only 30% of all the ash.
- In the wet-dry system, about 98% of total PCDD found in the ashes was in the fabric filter ash (which was 67% of total ash collected by the pilot plant), the balance being the wet-dry scrubber ash.

The PCDD homologue distribution in the hopper ashes is shown in Figure 21. Key observations are as follows:

- For each operating condition, the PCDD homologue distribution in the fabric filter ash is heavily skewed to the higher molecular weight compounds, particularly hexa, hepta and octa.
- The PCDD homologue distribution in the fabric filter ash is very similar to the homologue distribution in the inlet flue gas.
- The PCDD homologue distribution pattern for the dry reactor ashes is similarly skewed to the higher molecular weight compounds, but the skew is less pronounced.
- For the wet-dry reactor, there is only a slight skew towards the octas.

7.4 Furans in Hopper Ashes

PCDF concentrations (ng/g) in the hopper ashes collected in the three vessels are shown in Table 13.

TABLE 13 PCDF (ng/g) CONCENTRATIONS IN ASH

Operating Condition	Dry Mode				Wet-Dry Mode	
	110°C	125°C	140°C	>200°C	140°C	140°C +Recycle
Wet-Dry Scrubber Ash	10	12	4	5	5	8
Dry Scrubber Ash	87	36	68	22	N/A	N/A
Fabric Filter Ash	160	320	380	320	130	170

N/A = Not Applicable

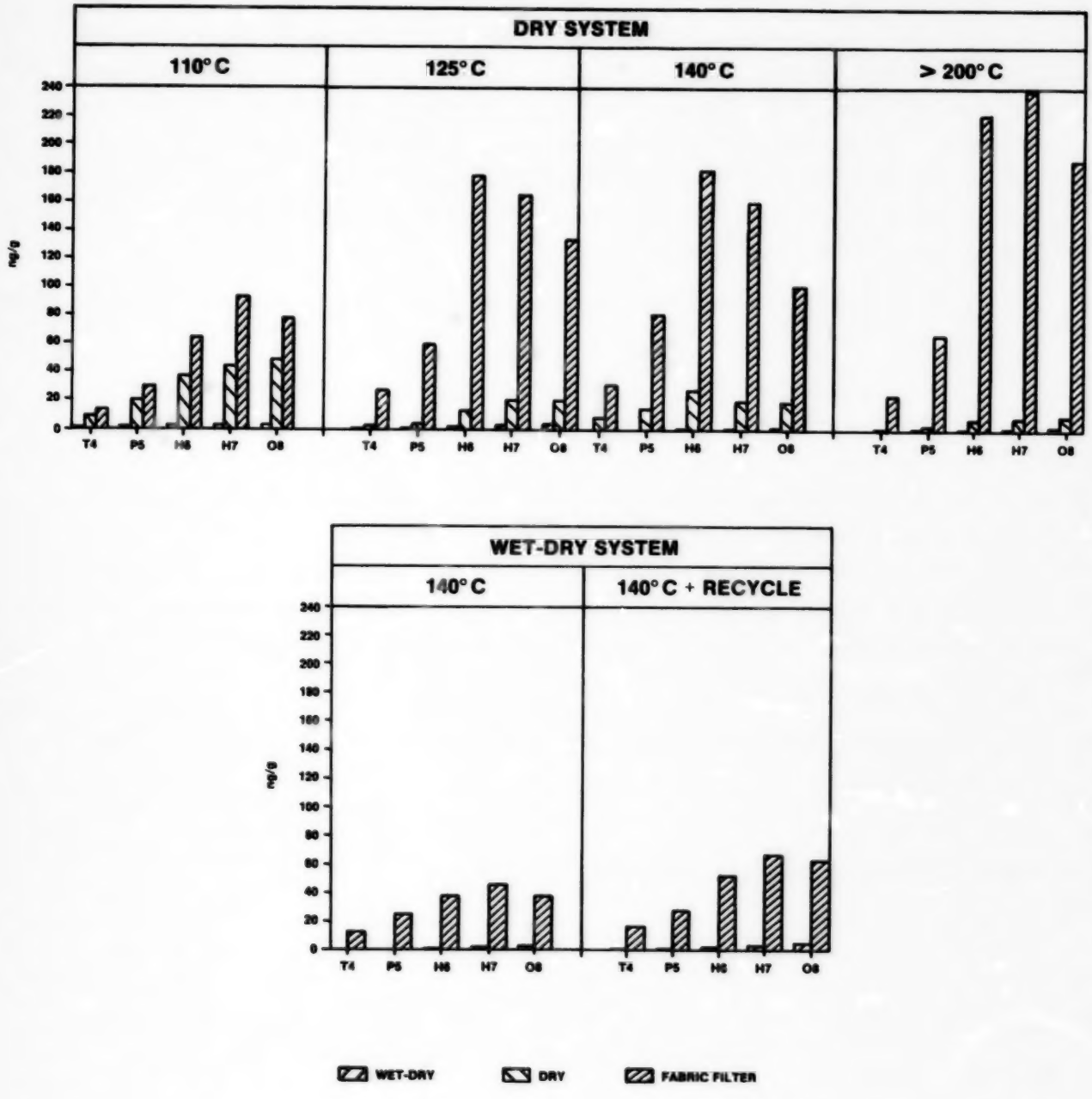


FIGURE 21 PCDD HOMOLOGUE DISTRIBUTION IN HOPPER ASHES

The PCDF concentrations in the dust samples are further illustrated in Figure 22.

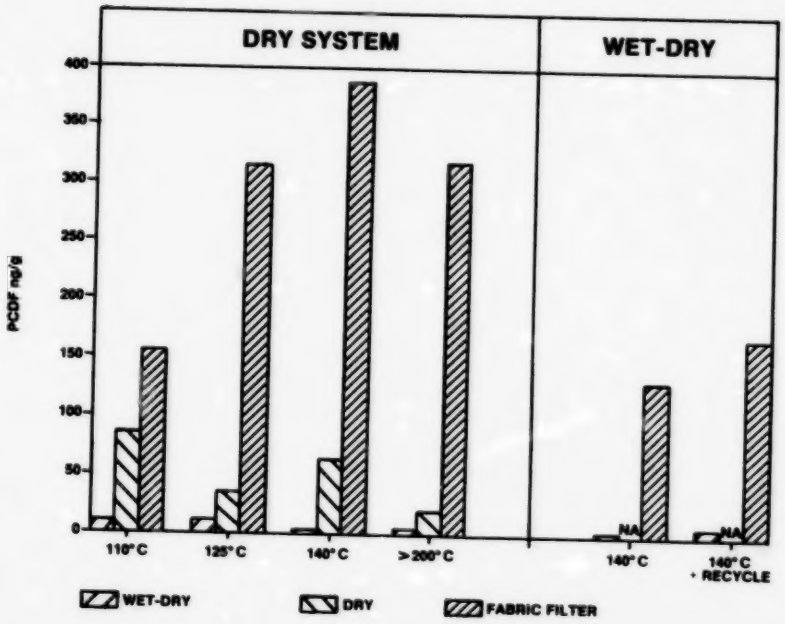


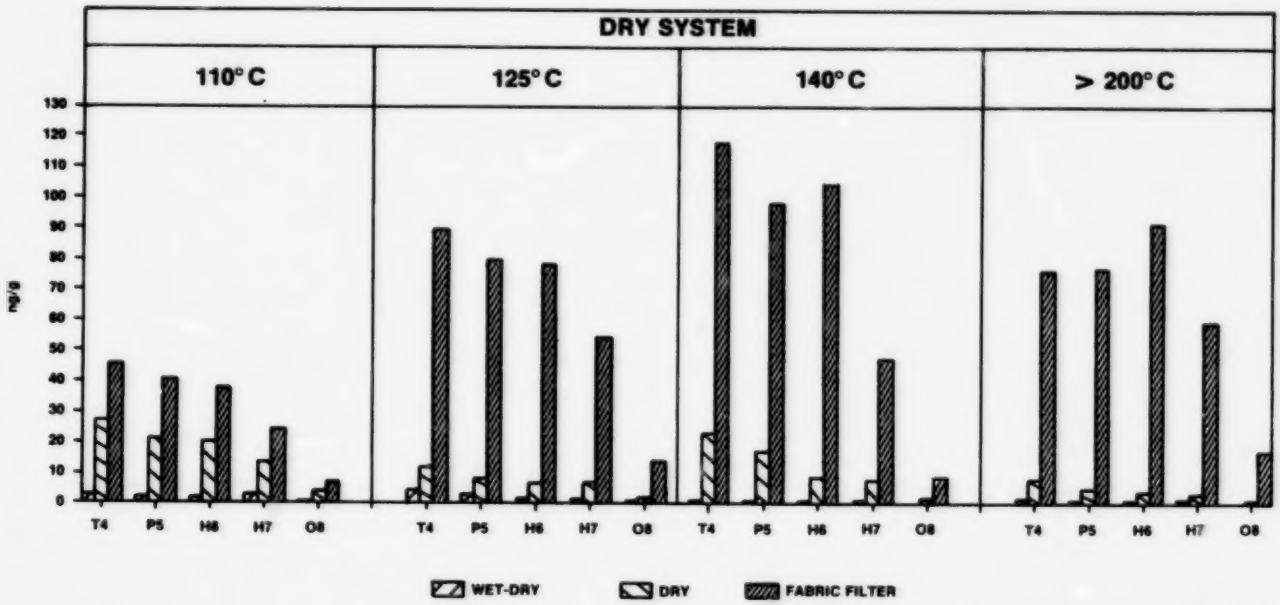
FIGURE 22 PCDF CONCENTRATIONS IN HOPPER ASHES

The PCDF distribution in the three ashes follows the same pattern as observed for PCDD:

- The highest concentration is found in the fabric filter for all test conditions.
- For the 110°C operating condition (lowest temperature), there is a shift to higher PCDF concentrations in the dry reactor ash and lower concentrations in the fabric filter ash compared to the other operating conditions.

The weighted average of PCDF based on concentration and relative proportion of total weight of each ash indicates the following:

- In the dry system, about 75% of the total PCDF found in the ashes was in the fabric filter ash and 22% was in the dry scrubber ash. In comparison, 30% of total ash collected by the pilot plant was the fabric filter ash and 40% was the dry scrubber ash, the balance being the gas cooler ash. Accordingly, as for dioxin, most of the furan in the ashes is in the fabric filter ash, which is only 30% of the total ash.



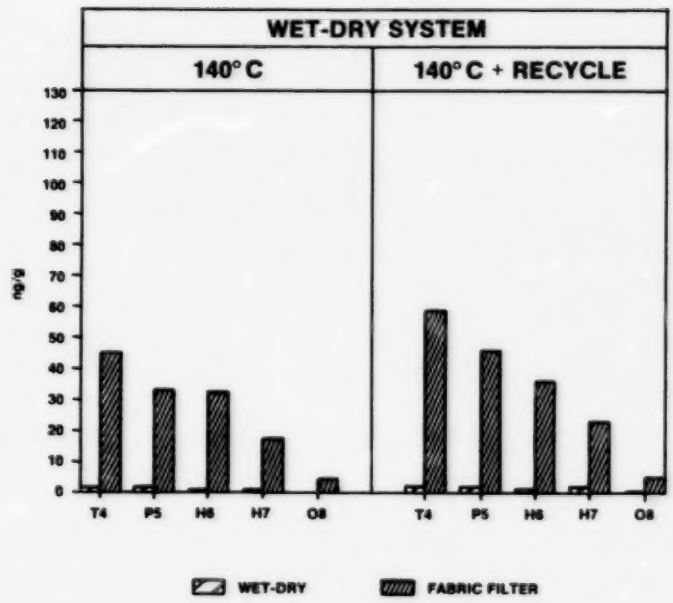


FIGURE 23 PCDF HOMOLOGUE DISTRIBUTION IN HOPPER ASHES

- In the wet-dry system, about 98% of all PCDF found in the ashes was in the fabric filter ash, which was 67% of total ash collected by the pilot plant, the balance being the wet-dry scrubber ash.

The PCDF homologue distribution for the ashes (shown in Figure 23) is skewed to the low molecular weight compounds for all test conditions and is similar to the PCDF homologue distribution for the inlet flue gas.

8 OTHER ORGANIC RESULTS

In addition to dioxins and furans, other trace organics are emitted in the flue gases from EFW facilities. These include chlorobenzenes (CB), chlorophenols (CP), polychlorinated biphenyls (PCB) and polycyclic aromatic hydrocarbons (PAH). The sampling trains used to collect dioxins and furans also collected these other trace organic compounds at the inlet, midpoint and outlet of the pilot plant. In addition, the ashes from the vessel hopper were analyzed for these other organics. To facilitate a review of the significant amount of data obtained, highlights of the other organics results are briefly summarized in tables and bar charts in this section.

8.1 Other Organics in Flue Gas

The overall removal efficiencies for chlorobenzenes (CB), chlorophenols (CP), polychlorinated biphenyls (PCB) and polycyclic aromatic hydrocarbons (PAH) are summarized in Table 14 for the six operating conditions tested.

TABLE 14 PERCENT REMOVAL OF OTHER ORGANICS

	Dry System				Wet-Dry System	
	110°C	125°C	140°C*	>200°C	140°C	140°C +Recycle
CB	95	98	98	62	>99	99
PCB	72	>99	>99	54	>99	>99
PAH	84	82	84	98	>99	79
CP	97	99	99	56	99	96

* Based on one test.

Key observations on removal efficiencies for the "other organics" are presented below:

- At 110, 125 and 140°C, the overall removal of other organic compounds by the pilot plant was significant.
- The highest temperature condition (>200°C, no gas cooling) resulted in lowest removal efficiencies for CB, PCB and CP. The opposite was found for PAH removal; the highest temperature condition provided highest removal (98%) for the dry system.

- The wet-dry system at 140°C provided the highest removal (>99%) of all six test conditions.

Figure 24 illustrates these points and provides concentration data (ng/Nm^3 @ 8% oxygen) in bar chart form:

- These bar charts indicate that most removal of the organics occurs in the fabric filter.
- At the higher temperatures of 140°C and >200°C, there was little or no CB removal across the scrubber.
- Ash recycle resulted in an increase in concentrations of CB, CP, PCB and PAH from inlet to mid-point (i.e., across scrubber) compared to the no-recycle operating condition. However, the emissions at the outlet were still reduced to the same relatively low level.

The footnotes in Figure 24 indicate that the pilot plant is capable of reducing emissions to the same level even when inlet concentrations are much higher than average.

8.2 Other Organics in Hopper Ashes

The relative concentrations of CB, PCB, PAH and CP in the various hopper ashes are illustrated in Figure 25. The distribution pattern of organic compounds in the various ashes follows a similar pattern as found for PCDD/PCDF: the highest concentrations occurred in the fabric filter ash and the concentration in the ashes increased as the flue gas went through the control system.

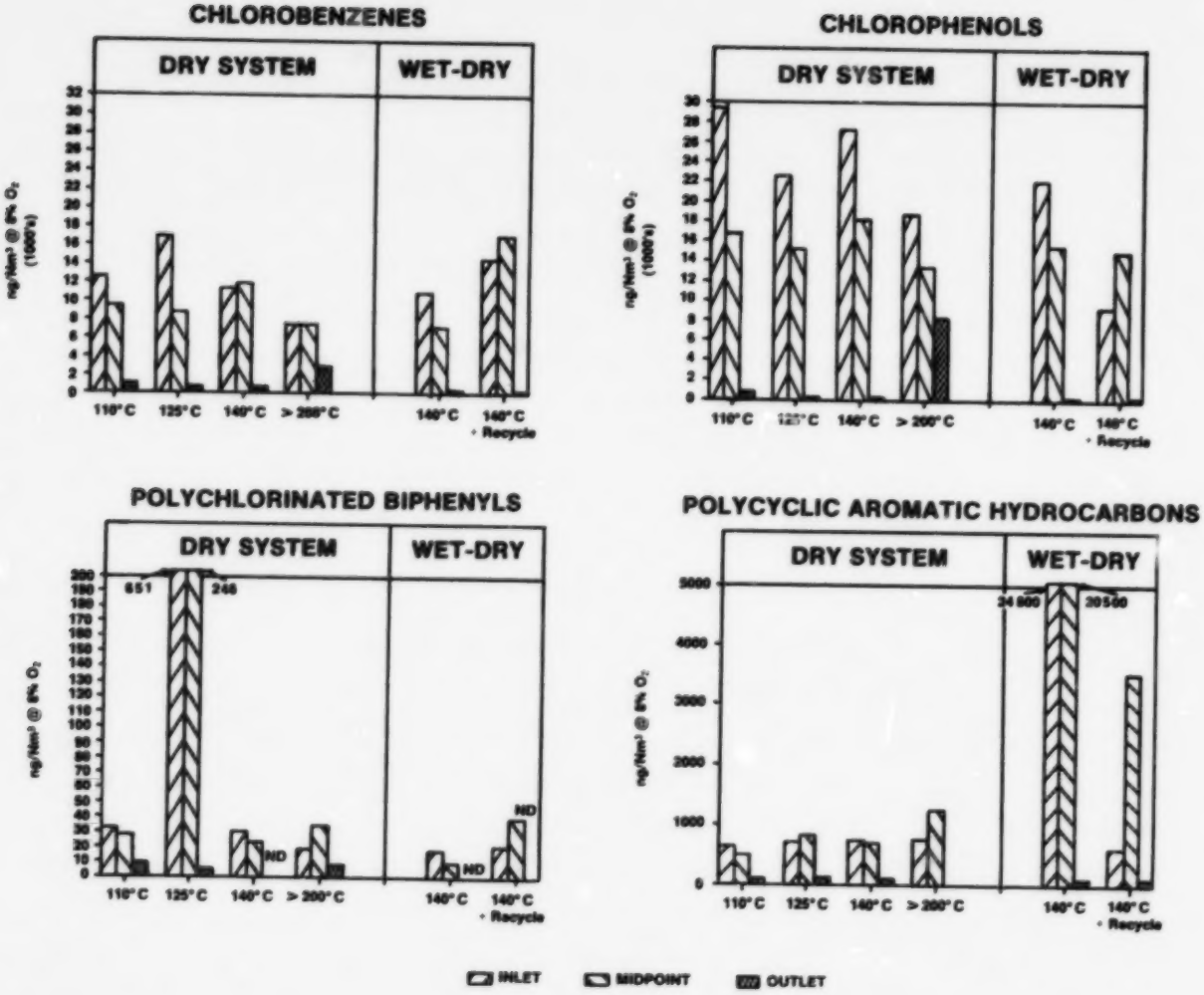


FIGURE 24 FLUE GAS CONCENTRATIONS OF CB, CP, PCB AND PAH

Note 1: At 125°C, PCB for PT3 was extremely high at the inlet (1300 ng/N^3 @ 8% O_2) compared to all other test runs. Nonetheless, the PCB level at the stack (8 ng/Nm^3) was as low as for all other operating conditions (ND to 12 ng/Nm^3 @ 8% O_2).

Note 2: At 140°C for the wet-dry mode (no recycle), the PAH level for PT8 was extremely high at the inlet (49 000 ng/Nm^3) compared to all other test runs. However, at the stack, the PAH was reduced to 78 ng/Nm^3 for PT8, which is similar to the results for all other test runs.

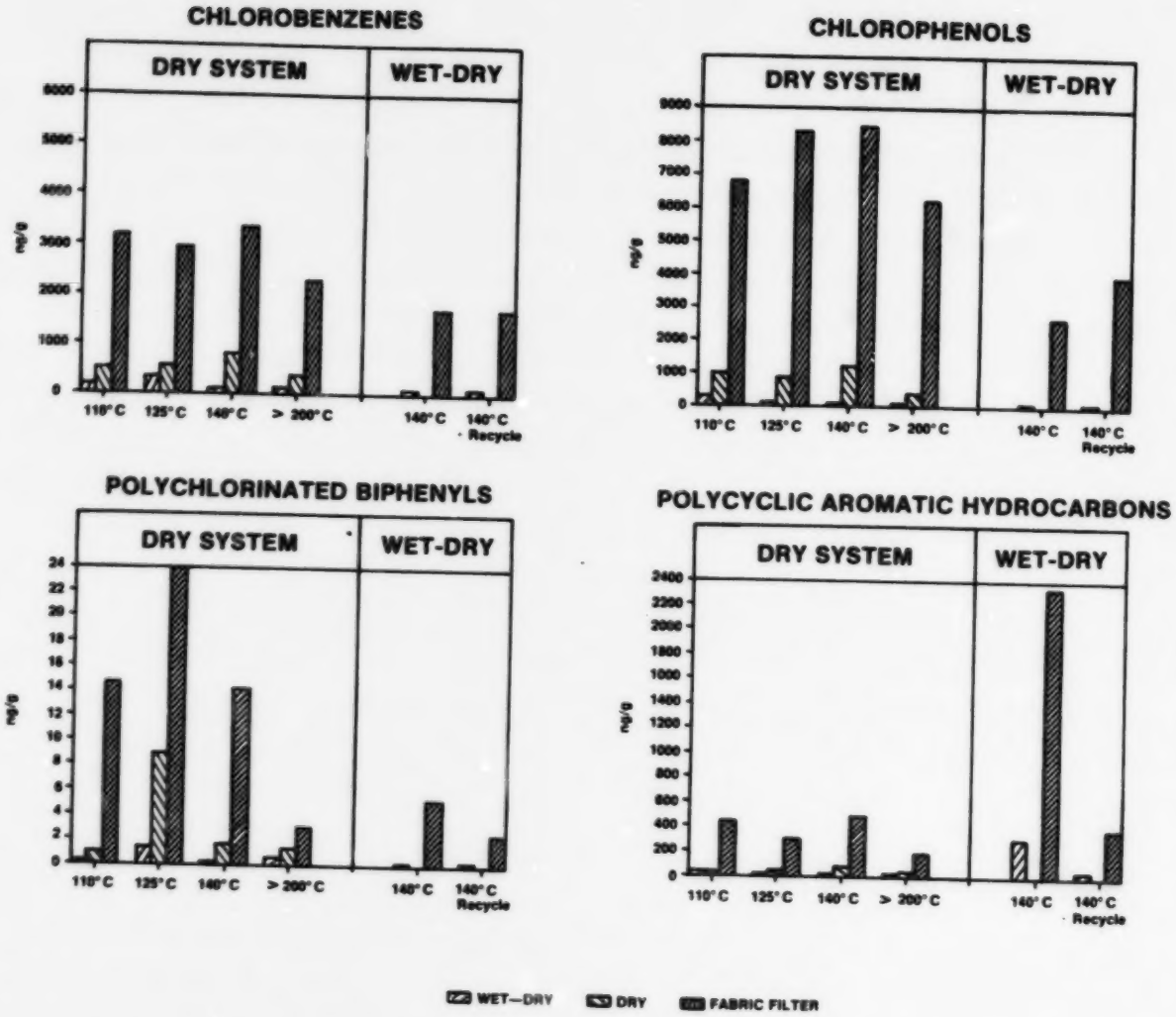


FIGURE 25 CB, CP, PCB AND PAH CONCENTRATIONS IN HOPPER ASHES

9 METALS RESULTS

9.1 Metals in Flue Gas

Metal analyses were performed on particulates collected at the inlet to the pilot plant and at the fabric filter outlet (stack). In all, 27 metals were detected and results for the 8 most significant ones, as established by previous NITEP studies, are presented in Table 15. In addition, dedicated sampling trains were run to sample mercury at the inlet and outlet. These results are also presented in Table 15.

TABLE 15 INLET/OUTLET METAL CONCENTRATIONS ($\mu g/Nm^3$ @ 8% O_2)

		Dry System				Wet-Dry System	
Metal	Location	110°C*	125°C*	140°C	>200°C	140°C	140°C +Recycle
Zinc (Zn)	Inlet	99 000	108 000	93 000	91 000	77 000	88 000
	Outlet	7	5	6	10	5	6
Cadmium (Cd)	Inlet	1 300	1 300	1 500	1 000	1 200	1 100
	Outlet	0.4	0.4	ND	0.6	ND	ND
Lead (Pb)	Inlet	41 000	44 000	34 000	35 000	36 000	34 000
	Outlet	4	3	5	6	1	6
Chromium (Cr)	Inlet	3 100	1 900	2 000	1 900	1 400	1 700
	Outlet	0.4	0.4	1	0.5	0.2	0.7
Nickel (Ni)	Inlet	1 000	1 800	1 300	800	700	2 500
	Outlet	1.3	0.4	0.7	2	1.3	2
Arsenic (As)	Inlet	150	100	130	80	110	130
	Outlet	0.02	0.04	0.04	0.07	0.04	0.03
Antimony (Sb)	Inlet	2 000	800	1 000	1 500	1 000	2 200
	Outlet	0.2	0.4	0.6	0.5	0.3	0.6
Mercury (Hg)	Inlet	440	480	320	450	190	360
	Outlet	40	13	20	610	10	19

Note : Concentrations rounded off for simplicity.
* Based on one test, except for mercury, which is based on two tests.
ND - Not detected

Major observations from Table 15 are as follows:

- The collection efficiency for all metals except mercury was greater than 99.9%. These results confirm the removal efficiencies (over 99%) reported for other dry scrubber/fabric filter installations, such as Sysav, Sweden (7), and Tsushima, Japan (8). Test results for the Munich Nord facility (dry scrubber/ESP) indicated greater than 98% removal of cadmium, lead and zinc, which is relatively high but less than the Flakt system using a fabric filter (9). Incinerators equipped with only electrostatic precipitators (no scrubber) are reported to have much lower metal removal efficiencies than systems with scrubbers and/or fabric filters (15).
- The collection efficiency for mercury ranged from 91 to 97% at all operating conditions, except for the high temperature (>200°C), during which no mercury was removed. These test results indicate that some cooling is essential for effective mercury removal. Results from the Sysav plant (dry scrubber/fabric filter) also showed low mercury emissions 12-65 $\mu g/Nm^3$ at 160°C (7), whereas results at Kempten, Germany (dry scrubber/ESP) showed high mercury emissions of 200-600 $\mu g/Nm^3$ at 220°C (9). The benefit of flue gas cooling for improved mercury removal has also been documented by Moller and Christiansen (11) and by Clarke (15).

9.2 Metals in Hopper Ashes

The material collected in the hopper of each vessel was also analyzed for metals. Concentrations of eight metals established as significant under previous NITEP studies are shown in the bar charts in Figure 26. Key observations are as follows:

- Six metals (Zn, Pb, Cd, As, Sb, Hg) followed the pattern observed for organics in the ashes. The fabric filter ash contained by far the highest concentration and the highest amount of the total metals removed by either the dry or wet-dry systems.
- Chromium and nickel showed highest concentrations in the scrubbers for the dry operating mode. The concentrations of chromium and nickel were similar in the scrubber ash and in the fabric filter ash for the wet-dry operating mode.

Hydrated lime, introduced in both the dry and wet-dry scrubbers to react with the acid gas, also contained trace amounts of metals. In order to account for the contribution of the metals present in the lime to the metals concentration in the various hopper ashes, a comparison is presented in Table 16.

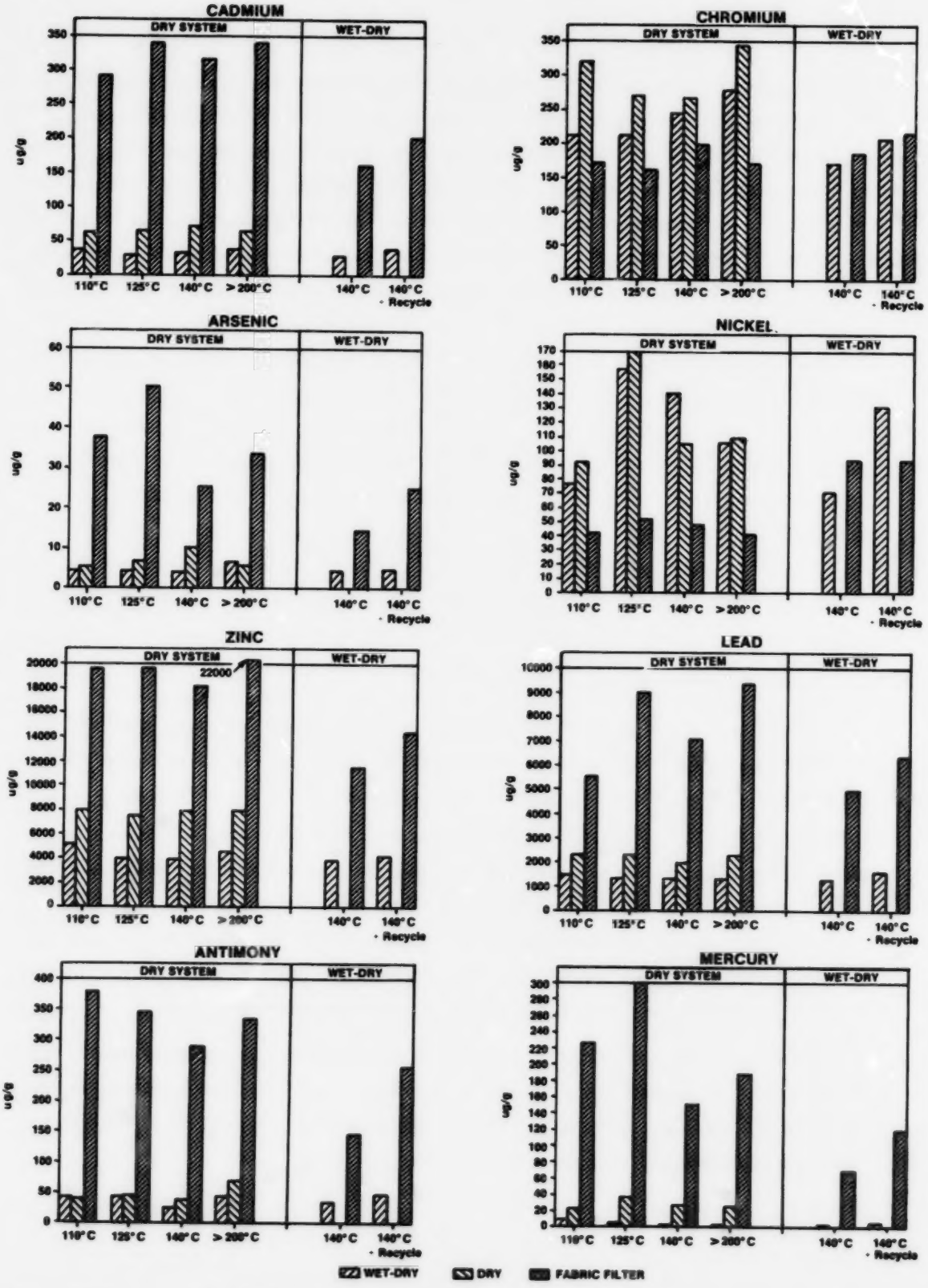


FIGURE 26 METALS IN HOPPER ASHES

TABLE 16 METAL CONCENTRATIONS IN LIME VERSUS METALS IN HOPPER ASH (µg/g)

Metal	Lime	Dry System Fabric Filter	Wet-Dry System	
			Wet-Dry Scrubber	Fabric Filter
Zinc	40	17 000	4 100	13 000
Cadmium	10	320	35	180
Lead	250	7 800	1 500	6 000
Chromium	40	170	190	200
Nickel	30	47	100	95
Antimony	ND	330	40	200
Arsenic	4	42	5	20
Mercury	ND	220	4	95

In the dry system, Flakt has determined, based on design considerations, that all the lime injected is conveyed to the fabric filter. Therefore, the following observations can be made from the data in Table 16:

- Approximately 50% of the fabric filter ash was made up of the lime injected into the system. It is possible that 15 to 30% of the nickel concentration in the fabric filter ash was due to nickel in the lime.
- Similarly, 5 to 10% of chromium and arsenic concentrations in the fabric filter ash could be attributed to these metals in the lime.
- Other metals were not present in significant enough quantities in the lime to account for their presence in the fabric filter ash.

In the wet-dry system, Flakt has determined based on design considerations that about 25% of the injected lime fell out in the wet-dry scrubber and 75% in the fabric filter. On this basis, it was estimated that 15% of the wet-dry scrubber ash and about 20% of the fabric filter ash is made up of lime injected into the system. Accordingly, the metals in the lime accounted for less than 6% of the metal content in the ashes, except for arsenic (wet-dry scrubber) for which the lime accounted for approximately 12%.

Overall, metal concentrations in the lime were not a significant contribution to the metal concentrations of the ashes in either system.

10 ACID GAS EMISSIONS

Acid gases, such as hydrogen chloride and sulphur dioxide, are an important emission parameter for EFW facilities. To adequately address these, continuous gas monitors for hydrogen chloride and sulphur dioxide were installed at the inlet, midpoint and outlet of the pilot plant. In addition, manual sampling trains for hydrogen chloride were used at all three sampling locations as a back-up to the continuous hydrogen chloride monitors, as discussed in section 5. The results for hydrogen chloride and sulphur dioxide removal from the flue gas are presented in this section.

10.1 Typical Hydrogen Chloride and Sulphur Dioxide Variations

Since the concentrations of hydrogen chloride and sulphur dioxide in incinerator flue gases are a function of the chlorine and sulphur content in the refuse, and since refuse composition is variable, concentrations in emissions can vary significantly over time, even within several minutes.

Figure 27 is provided to illustrate typical variations in hydrogen chloride and sulphur dioxide concentrations throughout a test period. At the inlet, hydrogen chloride varied by a factor of 2 and sulphur dioxide varied by a factor of 3, which is not uncommon for MSW incinerators. It is important to note in Figure 27 that the pilot plant was capable of accommodating these significant variations at the inlet and yet provided a relatively low and constant outlet concentration. For hydrogen chloride, there was good agreement between manual sampling train data and corresponding continuous monitors.

10.2 Acid Gas Data and Removal Efficiencies

Emissions data and collection efficiencies for hydrogen chloride and sulphur dioxide are summarized in Tables 17 and 18, respectively. The following key points have been observed:

- Hydrogen chloride can be reduced from the average concentration of 400 ppm at the inlet to less than 10 ppm at the outlet, provided that the flue gas is cooled to below 125°C in the scrubber.
- At the low temperatures (110°C and 125°C), hydrogen chloride collection efficiency was approximately 98%, which is significant. Similarly high removal efficiencies have been reported for the Sysav plant (7), the Munich-Nord facility (16) and for Tsushima Japan (8).

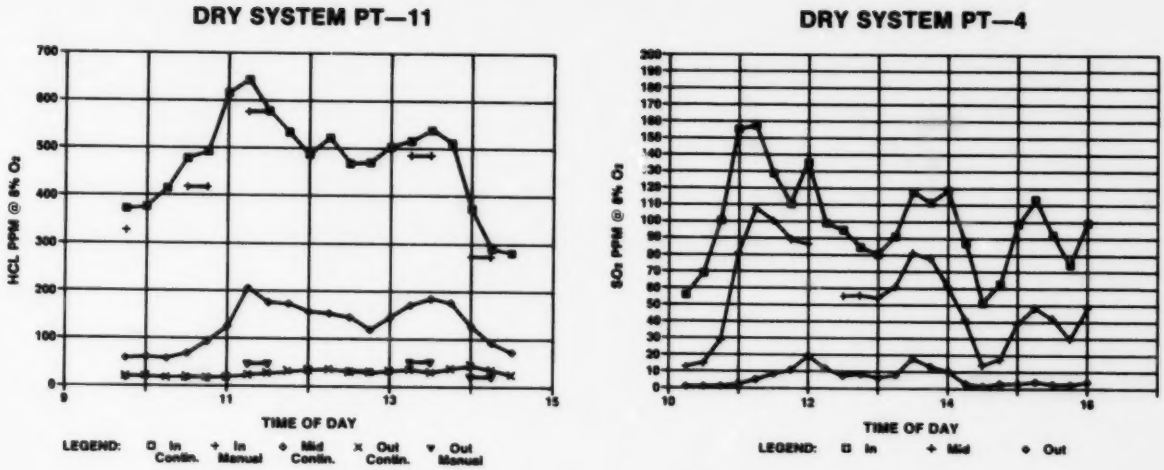

DRY SYSTEM PT—11
HCL PPM @ 8% O2
TIME OF DAY
LEGEND: In Contin. In Manual Mid Contin. Out Contin. Out Manual
DRY SYSTEM PT—4
SO2 PPM @ 8% O2
TIME OF DAY
LEGEND: In Mid Out

FIGURE 27 TYPICAL HYDROGEN CHLORIDE AND SULPHUR DIOXIDE VARIATIONS DURING PERFORMANCE TESTS

- At higher temperatures, hydrogen chloride removal was less effective: 77% @ >200°C and 91-94% at 140°C, clearly demonstrating an inverse relationship of temperatures to removal efficiency.
- Both systems showed similar performance for hydrogen chloride removal at 140°C.
- Recycling of ash appeared to have no significant effect on hydrogen chloride removal.
- Sulphur dioxide was reduced from an average concentration of 110-120 ppm at the inlet to less than 10 ppm at the outlet.
- Temperature appeared to have a significant impact on sulphur dioxide removal. At the high temperature condition (>200°C), sulphur dioxide removal efficiency was only 30%, whereas at the low temperatures (110 and 125°C) efficiencies exceeded 90%. These results are comparable to sulphur dioxide removal efficiencies reported by Hasselriss for other installations (4).
- At 140°C, there was no significant difference in performance between the two systems for sulphur dioxide removal.

TABLE 17 HYDROGEN CHLORIDE CONCENTRATIONS (@ 8% O_2) AND REMOVAL EFFICIENCIES

	Dry System				Wet-Dry System	
Flue Gas Temp. at F.F. Inlet	110°C	125°C	140°C	>200°C	140°C	140°C +Recycle
Stoichiometric Ratio	1.16	1.03	1.04	1.49	1.19	1.10
Inlet (ppm)	423[a]	464[b]	475[a,d]	392[b,d]	366[c]	470[a]
Midpoint (ppm)	15[a]	69[a]	129[a,d]	196[a,d]	149[a]	152[a]
Outlet (ppm)	7[a]	9[b]	29[a,d]	91[b,d]	29[a]	42[a]
Eff. to Midpoint (%)	96	85	73	50	59	68
Eff. Overall (%)	98	98	94	77	92	91

[a] Based on continuous gas monitors.
[b] Based on manual sampling (15-30 minute tests).
[c] Based on a combination of continuous gas monitors and manual sampling (15-30 minute tests).
[d] One test only.

TABLE 18 SULPHUR DIOXIDE CONCENTRATIONS (@ 8% O_2) AND REMOVAL EFFICIENCIES

	Dry System				Wet-Dry System	
Flue Gas Temp. at F.F. Inlet	110°C	125°C	140°C*	>200°C*	140°C	140°C +Recycle
Stoichiometric Ratio	1.16	1.03	1.04	1.49	1.19	1.10
Inlet (ppm)	119	118	99	117	106	106
Midpoint (ppm)	24	65	64	103	67	70
Outlet (ppm)	4	10	41	83	35	43
Eff. to Midpoint (%)	80	45	35	11	37	35
Eff. Overall (%)	96	92	58	29	67	60

* Based on one test.

- For the recycle condition in the wet-dry system, less lime was required to achieve approximately the same sulphur dioxide removal efficiency as without recycle. This point is further discussed with the presentation of Figure 30.

10.3 Stoichiometric Ratio and Lime Addition Rate

An important factor that affects the operating cost of gas scrubbing systems is the lime addition rate. One method of expressing the lime feed rate is the stoichiometric ratio (S.R.), which relates the amount of hydrated lime, $Ca(OH)_2$, fed into the scrubbers to the total amount of acid gases (hydrogen chloride and sulphur dioxide) present in the inlet flue gas. If there is enough lime to neutralize all the hydrogen chloride and sulphur dioxide, then the ratio is one (1). Higher than 1 indicates excess lime. In chemical terms, the stoichiometric ratio is the molar ratio of available reagent over the inlet hydrogen chloride and sulphur dioxide.

$$S.R. = \frac{\text{Moles of Available Lime}}{1/2 \text{ Moles HCl} + \text{Moles of } SO_2}$$

Lime availability was measured as 91% active lime used during the tests.

Throughout the performance test series, a target S.R. of 1.2 was selected. As shown in Tables 17 and 18, the target S.R. of 1.2 was relatively closely maintained for most of the test conditions. However, due to the variability of hydrogen chloride and sulphur dioxide at the inlet, the actual S.R. varied from the target value, particularly for the >200°C operating condition.

The four graphs in Figure 28 illustrate the relevance of stoichiometric ratio to hydrogen chloride removal and sulphur dioxide removal and demonstrate several key points:

- In all cases, for the ranges of acid gas concentrations monitored, the S.R. had very little effect on hydrogen chloride removal; temperature was a much more important factor.
- For the no gas cooling condition (>200°C), increasing the S.R. from 1.1 to 2.4 had virtually no effect on hydrogen chloride removal efficiency (77%).
- Temperature was the main factor in sulphur dioxide removal below 125°C; S.R. had very little or no effect on sulphur dioxide removal at 110°C and 125°C.
- S.R. had a very significant effect on sulphur dioxide removal at 140°C and >200°C.

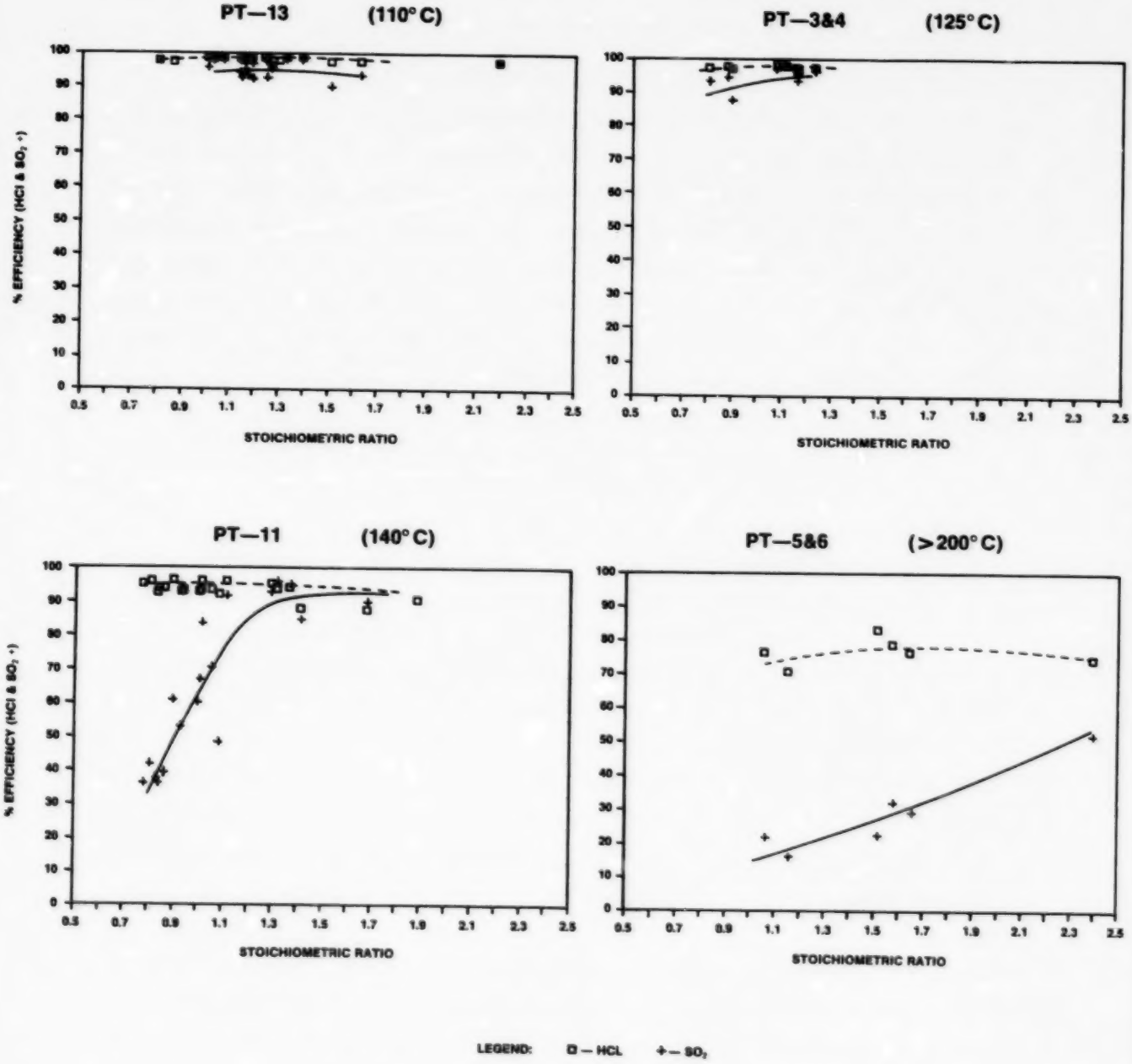


FIGURE 28 HYDROGEN CHLORIDE AND SULPHUR DIOXIDE REMOVAL EFFICIENCIES VERSUS STOICHIOMETRIC RATIO AT DIFFERENT TEMPERATURES FOR DRY SYSTEM

- Although sulphur dioxide removal was very significantly affected by S.R. at 140°C, good sulphur dioxide collection (90%) can be achieved if the S.R. is over 1.6. This would not be an economical way to operate.
- At the high temperature (>200°C), both S.R. and temperature seriously affected sulphur dioxide removal. Even at an S.R. of 1.6, efficiency was only 30%.
- For sulphur dioxide, the best removal (96%) occurred at the lowest temperature (110°C), for which S.R. was not important.

The importance of S.R. for sulphur dioxide removal is further illustrated in Figure 29. These curves show that above 125°C, SO_2 sulphur dioxide efficiency drops off rapidly. A higher S.R. reduces only the rate of the decline. For high sulphur dioxide removal, temperature control to below 125°C appears to be most economical.

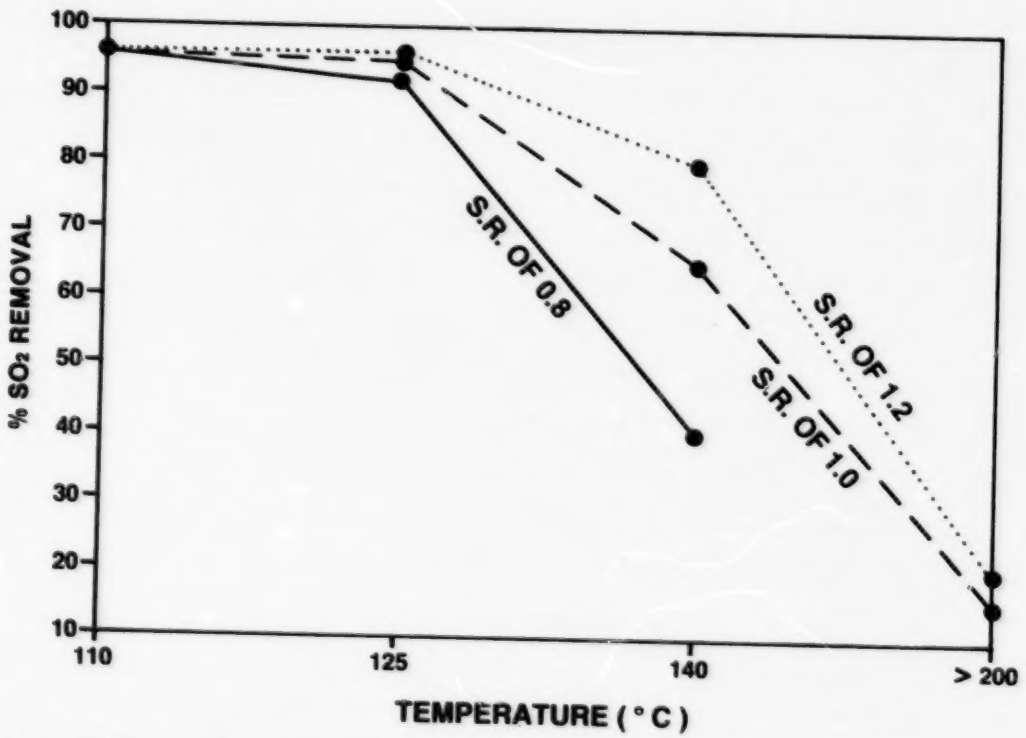


FIGURE 29 SULPHUR DIOXIDE REMOVAL VERSUS TEMPERATURE AT DIFFERENT STOICHIOMETRIC RATIOS

10.4 Effect of Ash Recycle

Figure 30 illustrates the beneficial effect of ash recycle on sulphur dioxide removal efficiency for the wet-dry system. The first graph presents the results with recycle (PT-9 and PT-10) and the second graph shows results with no recycle (PT-8). With recycle, the average S.R. was 1.10 and sulphur dioxide removal efficiency was 60%. On the other hand, with no recycle and an S.R. of 1.10 the removal efficiency was 46%. Therefore, ash recycling can improve sulphur dioxide removal efficiency. Recycle can provide the same sulphur dioxide removal efficiency as the no-recycle condition, using less fresh lime (i.e., a lower S.R.) This would also help to reduce the operating costs.

Ash recycle had no apparent effect on hydrogen chloride collection.

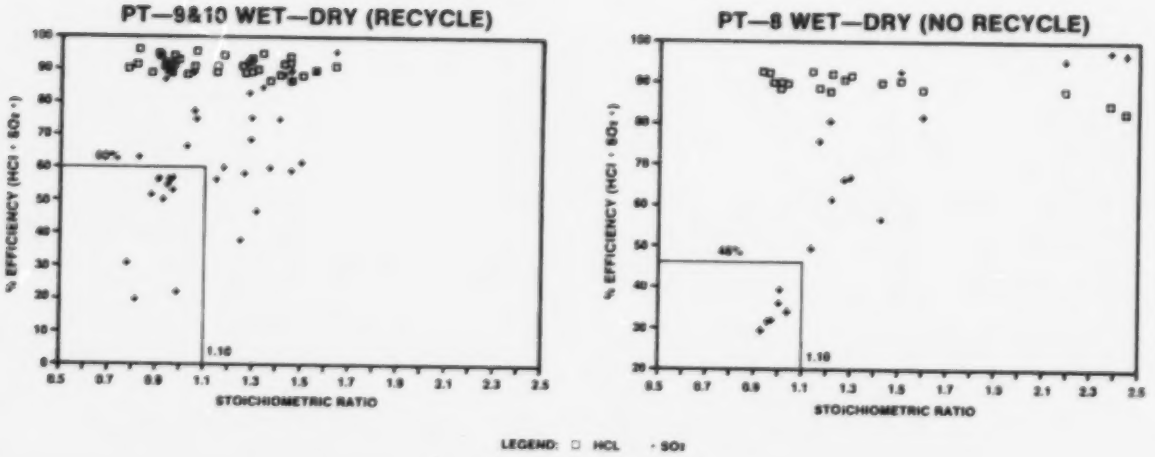


FIGURE 30 HYDROGEN CHLORIDE AND SULPHUR DIOXIDE REMOVAL VERSUS STOICHIOMETRIC RATIO WITH AND WITHOUT RECYCLE

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The following key conclusions have been drawn from the extensive test data obtained from the Flakt pilot plant system:

1) Both the wet-dry system using lime slurry and the dry system using powdered lime followed by a fabric filter are capable of high removal efficiencies for all pollutants of concern. In addition, no significant difference in removal efficiency was demonstrated by either system.

2) Cooling of the flue gas temperatures below 200°C was a key parameter in both systems for effective removal of hydrogen chloride, sulphur dioxide and mercury.

3) The removal efficiencies for dioxins (PCDD) and furans (PCDF) were very high. In all tests removal efficiencies exceeded 99% and, for most test runs, the concentrations of dioxins and furans after the control system approached the detection limits of the sampling and analytical methods employed.

4) The highest ash concentrations of PCDD and PCDF occurred in the fabric filter collector hopper and the lowest ash concentrations were found in the scrubber hopper. These results were anticipated based on the high removal efficiencies for PCDD and PCDF across the fabric filter collector.

5) Other trace organics, such as chlorobenzenes, polychlorinated biphenyls, chlorophenols and polycyclic aromatic hydrocarbons, were also efficiently removed (80 to 99%) by both systems when operated under cooled flue gas conditions.

6) Concentrations of the other trace organics in the various hopper ashes followed a pattern similar to that for PCDD/PCDF, whereby the highest concentrations occurred in the fabric filter ash.

7) Metal collection efficiencies generally exceeded 99.9% with both systems except for mercury. As noted in conclusion 2, flue gas cooling was an important parameter in maintaining a high removal efficiency for mercury.

8) For most of the selected metals (i.e., zinc, lead, cadmium, arsenic, antimony and mercury), the highest concentrations were in the fabric filter ash; this was not the case for chromium and nickel, where the concentrations were similar or higher in the scrubber ashes.

9) Control of acid gas concentrations can be maintained by either increasing the relative amount of lime to acid gas or by cooling the flue gases. However, flue gas cooling is a more economical approach since increasing lime utilization is more costly.

10) Ash recycle (i.e., fabric filter ash containing some residual unreacted lime) added to the fresh make-up lime was somewhat beneficial in providing the same sulphur dioxide removal efficiency as the no-recycle condition. By recycling ash, less fresh lime was used (i.e., a lower stoichiometric ratio), which would reduce the operating cost.

11) Two key independent variables tested were flue gas temperature control and stoichiometric ratio of lime to acid gas concentration. Temperature was found to be the most significant variable affecting removal efficiency.

11.2 Recommendations

Based on experience gained and results obtained during this series of tests, the following work is recommended for this type or similar air pollution control technologies:

1) Evaluate the effect, if any, on collection efficiency of higher levels of hydrogen chloride (1000-1500 ppm) and sulphur dioxide (300-500 ppm).

2) Evaluate the effect of temperatures between 140 and 200°C on removal efficiencies for mercury.

3) Assess the effect that lime addition may have on trace organics removal by testing both systems with lower lime addition rates than tested in this study, as well as with no lime addition.

4) Since the lime is an important part of annual operating costs, further evaluate the effect of recycling fabric filter ash to the reactors to reduce lime consumption for both operating modes.

The following observations may be helpful for anyone undertaking sampling for a similar air pollution control system:

1) The gas conditioning system for a continuous hydrogen chloride monitor operated under high moisture conditions requires special attention to prevent interference by condensed moisture.

2) Both continuous monitors and manual sampling trains for hydrogen chloride require special attention when operated at the inlet to the fabric filter where substantial amounts of lime are present. Since lime dust reacts with hydrogen chloride in the sampling equipment, a special removal system is necessary.

3) At the fabric filter outlet, extremely low concentrations of particulates were observed, which precluded the use of the filter component in the standard sampling train arrangement for a standard four-hour test period. Otherwise, an extension of the test period to a minimum of 24 hours would be required to ensure an adequate sample for metal analyses.

4) The fabric filter ash collection rate is difficult to measure accurately because the bag pulsing frequency affects the amount of ash dropping into the hopper. By employing a dedicated particulate sampling train at the inlet to the fabric filter, a more accurate determination can be made of the collection rate.

5) Due to possible air in-leakage across each vessel, both carbon dioxide and oxygen monitoring at all sampling locations (i.e., inlet, mid point and outlet) is recommended to allow for accurate correction of data to a common carbon dioxide or oxygen level.

6) Manual data entry from the data-logger to the computer for data reduction is time consuming. To save time and develop a "real time" display of testing results, all data logger output should be programmed for direct input into the computer for immediate data reduction.

7) A third-party quality assurance/quality control program is a very desirable asset for such an extensive sampling program.

REFERENCES

1. Report of the Ministers' Expert Advisory Committee on Dioxins, Joint Health and Welfare Canada/Environment Canada Publication, Ottawa, November 1983.

2. Environment Canada, The National Incinerator Testing and Evaluation Program: Two-Stage Combustion (Prince Edward Island) - Summary Report, Report EPS 3/UP/1, Ottawa, September 1985.

3. Martha Keating, National Dioxin Study Tier 4 - Combustion Sources - Final Literature Review, draft report by Radian Corporation for the U.S. Environmental Protection Agency, September 1985.

4. Hasselriis, Floyd. Technical Guidance Relative to Municipal Waste Incineration. Prepared for: Task Force on Municipal Incineration, New York State Department of Environmental Conservation, August 18, 1985.

5. Teller, A.J. and Lauber, J.D., Control of Dioxin Emissions from Incineration, presented at 76th Annual Meeting and Exhibition, Air Pollution Control Association. June 19-24, 1983, Atlanta, GA.

6. Nielsen, K. Krag, et al., Reduction of Dioxins and Furanes by Spray Dryer Absorption from Incinerator Flue Gas., presented at Dioxin 85. Bayreuth FRG, September 16-19, 1985.

7. Operational Studies at the Sysav Energy from Waste Plant, Malmo Sweden, Report of the Swedish Waste Management Association & the Swedish Environmental Protection Agency, June 1983 (translated by Flakt Canada Ltd.).

8. Air Emissions and Performance Testing of a Dry Scrubber (Quench Reactor) Dry Venturi and Fabric Filter System Operating on Flue Gas from Combustion of Municipal Solid Waste at Tsushima, Japan, prepared by Cooper Engineers for West County Agency of Contra Costa County, August 1984.

9. Carlsson, Kurt, Heavy Metals from Energy from Waste Plants - Comparison of Gas Cleaning Systems, Waste Management & Research (1986) 4,000 - 000.

10. Moller J.T. and Christiansen, O.B., Dry Scrubbing of Municipal Solid Waste Incinerator Flue Gas by Spray Dryer Absorption, presented at 77th Annual Air Pollution Control Association Meeting, June 1984.

11. Moller, J.T. and O. Christiansen, Dry Scrubbing of MSW Incinerator Flue Gas by Spray Dryer Absorption: New Developments in Europe, presented at 78th Annual Air Pollution Control Association Meeting, June 1985.

12. H.J. Regler, Rezirkulation von Calzium Hydroxid Bei Einem Trockenen Rauchgasreinigungsverfahren, presented at conference "Mullverbrennung und Rauch Gasreinigung", Berlin, November 1985.

13. Division of Air Resources, Bureau of Toxic Air Sampling, Emission Source Test Report, Preliminary Report on Westchester Resco, New York State Department of Environmental Conservation, January 8, 1986.

14. Eriksson K., and Bergstrom J., Flakt internal technical report MKS-85/107.

15. Clarke, M.J., Emission Control Technologies for Resource Recovery, presented at Symposium on Environmental Pollution in the Urban Area, Brooklyn Polytechnic University, March 1986.

16. Hahn, Jeffrey L. et. al., Air Emission Test of a Deutche Babcock Anlagen Dry Scrubber System at the Munich-North Refuse-Fired Power Plant; presented at the 78th Annual Meeting of the Air Pollution Control Association, June 16-21, 1985, Detroit, MI.

APPENDIX

SYMBOLS, ABBREVIATIONS AND HOMOLOGUES OF POLYCHLORINATED DIBENZODIOXINS AND DIBENZO FURANS

APPENDIX

SYMBOLS AND ABBREVIATIONS

SI Prefixes

Prefix	Symbol	Multiplication Factor	Exponent
mega	M	1 000 000	= 10^6
kilo	k	1 000	= 10^3
hecto	h	100	= 10^2
deca	da	10	= 10^1
unit	-	1	= 10^0
deci	d	0.1	= 10^{-1}
centi	c	0.001	= 10^{-2}
milli	m	0.001	= 10^{-3}
micro	μ	0.000 001	= 10^{-6}
nano	n	0.000 000 001	= 10^{-9}
pico	p	0.000 000 000 001	= 10^{-12}

Units

Symbol	Unit	Comments
Mass/Weight		
g	gram	-
tonne	metric tonne	1 tonne = 1 Mg
lb	pound	1 pound = 453.592 g
Length		
m	metre	-
ft	foot	1 ft = 0.3048 m
Volume		
L	litre	-
m^3	cubic metre	1 m^3 = 1000 L
Nm^3	normal cubic metre	at standard conditions 25°C, 101.325 kPa
cm^3	cubic centimetre	
ft^3	cubic foot	1 ft^3 = 0.02832 m^3

SYMBOLS AND ABBREVIATIONS (Cont'd)

Units (cont'd)

Symbol	Unit	Comments
Time		
s	second	-
m (min)	minute	1 min = 60 s
h (h)	hour	1 h = 3600 s
Temperature		
°C	degree Celsius	-
°F	degree Farenheit	-
Pressure		
bar	bar	-
Pa	Pascal	1 Pa = 10^{-5} bar
Acronyms		
ASTM	American Society for Testing and Materials	
NITEP	National Incinerator Testing and Evaluation Program	
EPA	Environmental Protection Agency	United States of America
ASME	American Society of Mechanical Engineers	
Sampling and Analytical Terminology		
XAD-2	Amberlite Resin used to absorb organics	
GC	Gas Chromatography	
MS	Mass Spectrometry	
ECD	Electron Capture Detector	
MID	Multiple Ion Detection	
MM5	Modified Method 5	
CT	Characterization Test	
PT	Performance Test	
QA/QC	Quality Assurance/Quality Control	

SYMBOLS AND ABBREVIATIONS (Cont'd)

Compounds

PCB	Polychlorinated Biphenyls
PAH	Polycyclic Aromatic Hydrocarbons
THC	Total Hydrocarbons
TOX	Total Organic Halides
CP	Chlorophenols
CB	Chlorobenzenes
CO	Carbon Monoxide
CO_2	Carbon Dioxide
O_2	Oxygen
SO_2	Sulphur Dioxide
HCl	Hydrogen Chloride
TSP	Total Suspended Particulate or Particulate Matter
NaOH	Sodium Hydroxide
$KMnO_4$	Potassium Permanganate
H_2O	Water
H_2SO_4	Sulphuric Acid
HNO_3	Nitric Acid
Na_2SO_4	Sodium Sulphate
$HClO_4$	Perchloric Acid
$Ca(OH)_2$	Calcium Hydroxide

Metals

Cd	Cadmium
Be	Beryllium
Mo	Molybdenum
Ca	Calcium
V	Vanadium
Al	Aluminum
Mg	Magnesium
Ba	Barium
K	Potassium
Na	Sodium

SYMBOLS AND ABBREVIATIONS (Cont'd)

Metals (Cont'd)

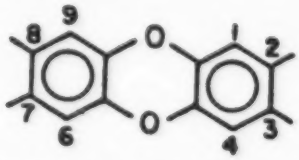
Zn	Zinc
Mn	Manganese
Co	Cobalt
Cu	Copper
Ag	Silver
Fe	Iron
Pb	Lead
Cr	Chromium
Ni	Nickel
Si	Silicon
Ti	Titanium
B	Boron
P	Phosphorus
Hg	Mercury
As	Arsenic
Sb	Antimony
Bi	Bismuth
Se	Selenium
Te	Tellerium
Sn	Tin

Miscellaneous

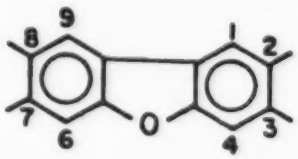
ND	Not Detected
ppm	part per million
°	Degree (angle or temperature)
±	plus or minus
<	less than
>	greater than
ID	Induced Draft (fan)

Polychlorinated Dibenzodioxins and Dibenzofurans

Polychlorinated dibenzodioxins* (PCDDs) are a family of compounds consisting of two benzene rings joined by two oxygen atoms and having from one to eight chlorine atoms attached around the rings (see figure). There are 75 chlorinated dioxins which differ in the positions or number of chlorine atoms. The tetrachlorinated dibenzodioxins (TCDDs) are the 22 different dioxins (isomers) having four chlorine atoms. The isomer known as 2,3,7,8-TCDD has chlorine atoms at the locations numbered 2,3,7 and 8. The polychlorinated dibenzofurans (PCDFs) are a very similar family of compounds differing in that only one of the bonds between the benzene rings contains an oxygen atom. The nomenclature for the chlorinated dibenzofurans is completely analogous to that for the dibenzodioxins.



Polychlorinated Dibenzodioxins
(PCDDs)



Polychlorinated Dibenzofurans
(PCDFs)

Polychlorinated dibenzo-*p*-dioxin homologues:

T4CDD	Tetrachlorodibenzo-*p*-dioxin
P5CDD	Pentachlorodibenzo-*p*-dioxin
H6CDD	Hexachlorodibenzo-*p*-dioxin
H7CDD	Heptachlorodibenzo-*p*-dioxin
O8CDD	Octachlorodibenzo-*p*-dioxin

Polychlorinated dibenzofuran homologues:

T4CDF	Tetrachlorodibenzofuran
P5CDF	Pentachlorodibenzofuran
H6CDF	Hexachlorodibenzofuran
H7CDF	Heptachlorodibenzofuran
O8CDF	Octachlorodibenzofuran

---

* The full chemical name is polychlorinated dibenzo-*para*-dioxins or polychlorinated dibenzo-*p*-dioxin.